Response to Peer Review of:

Ricardo, Inc. Draft Report, "Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe"

November 29, 2011

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Acknowledgements

This report was prepared by Systems Research and Applications Corporation (SRA) for the U.S. Environmental Protection Agency (EPA), Office of Transportation and Air Quality under EPA Contract No. EP-C-11-007, Work Assignment 0-12, at the direction of EPA Work Assignment Manager Jeff Cherry. The material in this report represents the combined effort of SRA, Ricardo Inc. (as subcontractor to SRA), and staff from the U.S. Environmental Protection Agency that have been involved in this project.

Introduction

As the U.S. Environmental Protection Agency (EPA) develops programs to reduce greenhouse gas (GHG) emissions and increase fuel economy of light-duty highway vehicles, there is a need to evaluate the costs of technologies necessary to bring about such improvements. Some potential technology paths that manufacturers might pursue to meet future standards may include advanced engines, hybrid electric systems, and mass reduction, along with additional road load reductions and accessory improvements. One method of assessing the effectiveness of future light duty vehicle (LDV) technologies on future vehicle performance and GHG emissions in the near-term timeframe is through modeling assessments.

Ricardo, Inc. developed such simulation models and documented the relevant technologies, inputs, modeling techniques, and results of the study in its April 6, 2011, Draft Report, *"Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020–2025 Timeframe"* contained in the supplement of this document. Ricardo performed this work under a subcontract to Systems Research and Applications Corporation (SRA) under EPA contract EP-W-07-064. The report documented both LDV technologies likely to be available within the specified timeframe and the development of a visualization tool that allows users to evaluate the effectiveness of such technology packages in both reducing GHG emissions and their resulting effect on vehicle performance. The technologies addressed including conventional and hybrid powertrains, transmissions, engine technologies and displacement, final drive ratio, vehicle weight, and rolling resistance were examined for seven light-duty vehicle classes.

EPA then contracted with ICF International (ICF) to coordinate an external peer review of the inputs, methodologies, and results described in this report. The review was broad and encouraged reviewers to address the adequacy of the model's inputs and parameters, the simulation methodology, and its predictions as well as the report's completeness and adequacy for the stated goals. Through this process, EPA was able to conduct a thorough peer review with reviewers representing subject matter expertise in advanced engine technology, hybrid vehicle technology, and vehicle modeling.

The following five individuals agreed to participate in the peer review:

1. Dr. Dennis Assanis, University of Michigan
2. Mr. Scott McBroom, Fallbrook Technologies, Inc.
3. Dr. Shawn Midlam-Mohler, The Ohio State University
4. Dr. Robert Sawyer, University of California at Berkeley
5. Mr. Wallace Wade, Ford Motor Company (Retired)

ICF provided reviewers with the following materials:

- Draft project report by Ricardo (2011);
- The Ricardo Computer Simulation tool;
- The Peer Reviewer Charge to guide their evaluation; and
- A template for the comments organized around the Peer Reviewer charge.

The consensus of the first review based on these materials was that reviewers needed more information than was provided in the Ricardo report to complete their review. EPA then requested a second round of peer review in which the peer reviewers were provided more detailed information. Ricardo provided 45 additional PowerPoint presentations and documents, which included more clarity on assumptions, pictures of engine maps, and other pertinent information. Only three of the original reviewers were available to participate in the second round of peer review:

1. Mr. Scott McBroom, Fallbrook Technologies, Inc.
2. Dr. Shawn Midlam-Mohler, Ohio State University
3. Dr. Robert Sawyer, University of California, Berkeley

More detail about the review is available in the ICF report entitled: *Peer Review of Ricardo, Inc. Draft Report, "Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe"* (September 30, 2011) contained in the supplement of this document. In response to this peer review, EPA issued a follow-on work assignment to SRA (and Ricardo as SRA's subcontractor) to address the peer review comments. The response to the peer review involved:

- Significant revisions to the draft report
- A user's guide to the Data Visualization Tool referenced in the report
- Specific responses to each of the peer review comments

The final version of the report includes numerous changes, especially in Sections 4 and 6 of the report, and new appendix and attachment materials. The revised report serves as the primary response to the overall peer review input. The final report with all revisions is dated November 14, 2011. In addition, Ricardo, Inc., as a subcontractor to SRA, is preparing a separate user's guide to the tool. The final guide will be made available to the public by EPA upon final approval of that document.

Finally, this companion report presents item-by-item responses to each individual comment raised in the peer review. The responses reflect discussions about each of the comments between EPA, SRA, and Ricardo. Many of the responses refer to the specific revisions within the report that represent the decision on how best to address the comment. Others provide a brief response in the event that the comment was handled through the general process of revising the report, where the comment can be answered with a clarifying response but without any corresponding report revision, or where EPA and the project team determined that no revision was warranted given the nature of the comment within the context of the study.

The comments in the following Table 1 are the same as those presented in Table 2 to ICF's report of the peer review findings. In developing the responses, we added a column with a report section reference, if applicable. Where no specific report section applies to the specific comment, we used "General" in that column. We then sorted the comments based on this column.

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments		14	Including the membership of the advisory committee would be appropriate.	The Advisory Committee is described in Chapter 1.	1
Completeness	Section 3.3 Technology Selection Process	124	Who is on the Advisory Committee? Is it independent? How did the program team come up with the comprehensive list of potential technologies? (From the phone call it sounded like it was based on what models Ricardo had in their library. This is concerning.)	The Advisory Committee is described in Chapter 1.	1
Inputs and Parameters	Section 3.2 Ground Rules for Study	63	The vehicle and technology selection process needs further discussion. My experience in these large simulation studies is that the vast majority of the time needs to be spent on the selection and once selected agreeing upon the model/data.	EPA and Ricardo appreciate the comment; see section 3 of the final report. No further response is required.	3.2
Completeness	Section 3.3 Ground Rules	123	How did the group arrive at the seven vehicles? While it show comprehensiveness, it's possible to see that there could be some overlap. If one looks at the engine and transmissions packages available in these vehicles already you can see the overlap. Reducing the number of vehicles might save on the number of runs you'll need to make.	Some overlap is expected as the utility of these vehicles varies based on vehicle class. The 5 center vehicle classes are carryover from the previous work and were used for consistency moving forward into the future technologies. The smallest class was added to reflect this growing segment and the class 3 truck was added to help EPA bridge the gap between light and heavy duty analysis.	3.3
Completeness		128	Regarding "Current (2010) maturity of the technology", how was maturity ranked?	Ricardo subject matter experts provided the rankings for the various technologies.	3.3

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Simulation methodology	Section 3.4 CSM Approach	77	Is the CSM approach used in other applications? If so it would be helpful to give citations. If it was developed by Ricardo, that should be stated. The discussion refers to physics based models, but other than that very little about the type of modeling is discussed. I recall on the phone call that lumped parameter models were mentioned. There is no discussion of that.	In the final report, Ricardo has added significant details of the modeling and provided graphics to illustrate a number of the issues. As for CSM, it is a standard approach to analyzing complex systems with many variables, and Easy5 as a tool for CSM has been used in many applications, including rocket and aircraft design, as well as automotive design and modeling applications. The report focuses on the findings of the study, and not the validation of CSM as an approach.	3.4
Other Comments		19	The characterization of the modeling methodology as objective and "scientific" suggests that the simulation is composed of rigorous, first-principle expressions for the various phenomena without using "correlations", "empirical formulas", and "phenomenological models". Are these conditions truly met? For instance, in many cases, steady-state dyno test data are the basis of an engine map featuring a certain technology. In other cases, available data were scaled based on empirical/proprietary factors and modifiers. The report should not characterize the study as "scientific" unless data uncertainty is discussed and shown in appropriate situations. For example, Table 7.1 presents comparisons between simulated and actual vehicle fuel economy performance. Given the various subjective assumptions involved in the analysis, the authors should comment whether the noticeable differences in certain cases are significant.	Complex systems modeling is a recognized scientific-based approach to analysis of complex systems, so the language used in the draft report remains in the final report. However, the point is taken that the study takes this science-based modeling approach, and applies certain assumptions and other factors based on empirical considerations, some of which are qualitative and potentially subjective.	3.4, 7.1, 8

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Inputs and Parameters		70	No mention or consideration of cylinder deactivation technologies. This seems like pretty low hanging fruit, even on downsized boosted engines, especially if you deploy DVA.	Ricardo subject matter experts along with the study group and engine manufacturers could not justify cylinder deactivation on four cylinder engines at this time due to significant NVH and durability issues. Cylinder deactivation was included in the previous study.	4
Completeness		126	Why wasn't HCCI technology considered? From the publications this seems to be a candidate for production in the next 10 yrs.	Ricardo subject matter experts along with the study group could not justify this technology for full range vehicle applications. HCCI was included in the previous study.	4
Completeness	Section 4. Technology Review and Selection	127	Regarding qualitative evaluation of technology "Potential of the technology to improve GHG emissions on a tank to wheels basis", since this was a qualitative assessment I think it would be better to include well to wheels.	A well to wheels analysis was beyond the scope of this study.	4
Completeness		129	Citations required for statement " SI engine efficiency to approach CI efficiency in the time frame considered" This represents relatively large gains in SI technology compared to CI, however EU and Japanese engine companies are making big improvements on CI as well.	The technology details in Section 4 are a basis for this general expectation, which clarifies why the study focused significant energy on the SI category. Ricardo's professional judgment is that, given the emission standards, this statement is a reasonable expectation for the study time frame.	4

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Engine Models	256	The description of the derivation of the engine models in the report was, at best, vague, as illustrated by the two examples below: Example 1: Stoichiometric DI Turbo The current research engines of this configuration were reported to be the Sabre engine developed by Lotus and the downsized concept engine developed by Mahle. Since the engine modeled in the Ricardo report had a peak BMEP of 25-30 bar and used series-sequential turbochargers, the Sabre engine is not applicable since it only had a peak BMEP of 20 bar and used a single stage turbocharger (Coltman et a., 2008; Turner et al., 2009). On the other hand, the Mahle engine appeared to be directly applicable, since it had a peak BMEP of 30 bar and used series-sequential turbocharging (Lumsden et al., 2009). Since Lumsden et al. provided the BSFC map for this engine, shown below, it is not clear why the Ricardo report could not have shown this map, or a map derived from this one, and then described how it was derived and/or combined with other maps to provide the model used in the report. (See Exhibit 3)	See revised section 4 for additional details and engine technology examples.	4
Other Comments	Engine Models	258	The report should explain whether the engine model is only a map of BSFC vs. speed and load, or if the engine model includes details of the turbocharger, valve timing, and control algorithms for parameters such as air/fuel ratio, spark/injection timing, EGR rate, boost pressure, and valve timing.	All of these parameters are inherent to the engine map. See revised section 4.	4

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Engine Models	259	Advanced valvetrains were included in many of the advanced engines (page 12). However, the method for applying these advanced valvetrains to the engine maps was not provided. Also, no description of the control strategy for these valvetrains was provided. The report did not provide a description of how the reduction of pumping losses with an advanced valvetrain was applied to a downsized engine that already had reduced pumping losses. Therefore, no assessment of how the model handled synergies could be made.	Section 4 has been revised with this additional information.	4
Recommendations	Engine Models	311	Describe what the "other inputs" are to the engine maps.	See Chapter 4.	4
Inputs and Parameters	Section 4	64	There was no model data provided. Engine maps, transmission efficiency maps, battery efficiency maps etc need to be in the Appendices. The black box nature of the inputs is disconcerting.	The final report adds detail on these types of issues; see especially changes to sections 4 and 6.8.	4, 6.8
Inputs and Parameters	Engine Models	306	The engine model is the most important element in successfully modeling the capability of future vehicles, since it is the responsible for the largest loss of energy. It is also one of the most difficult aspect to predict since it involves many complicated processes (i.e. combustion, compressible flow) which must be considered in parallel with emissions compliance (i.e. in-cylinder formation, catalytic reduction.) Because of this, this sub-model must be viewed with extreme scrutiny in order to ensure quality outputs from the model.	See revised section 4.1.	4.1
Inputs and Parameters	SI Engine Maps and Diesel Engine Maps	395	For the 2020 engine maps, there is insufficient detail in this presentation on how the maps were generated. Getting accurate simulation requires careful validation of the model as well as the data in the model – these engine maps are not sufficiently well documented for me to make a judgment on their suitability for the overall goal of the simulator. I am well aware that these future engines do not exist, but there had to be some process of generating these engine maps. Without more information on this process it is simply not possible to comment on their accuracy.	See revised section 4.1.	4.1

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Completeness	Sections 4.1 and 4.2	130	There's no descriptions of the models. There are only descriptions of the technologies and their perceived benefits. The reader has to assume that the same modeling approach was used to model each technology, but I know from personal experience this is very difficult and most likely not the case.	The final report adds details on the study's modeling approach. See sections 4.1 & 4.2, which also reference chapter 6. Engine modeling is described in Section 6.3. The revised Figure 6.1 provides an overall vehicle diagram.	4.1, 4.2, 6.3
Recommendations	Specific recommendations for improvements	238	Provide descriptions of the algorithms used for engine control, transmission control, hybrid system control, and accessory control.	See revised sections 4.1 and 6.	4.1, 6
Simulation methodology	Engines and Engine Models (Sections 4.1 and 6.3)	31	Specific suggestions regarding models that need more detailed coverage: The report lacks detail on the specifics on the different engine design and operating choices. For instance, what was the compression ratio (and limit) that was used? What is the equivalence ratio, or range considered, for the lean burn engine? How much EGR has been used across the speed and load range? What constraints, if any, were applied to the simulations to account for combustions limitations such as knock and flammability limits? The NOx aftertreatment/constraints section could also be expanded.	The final report adds detail on the compression ratio, and the use of 0 for LBDI. The report also details the range of EGR used, and expands on the NOx treatment/constraints. The final report also adds a chart for the switching zone, and includes text concerning the exhaust temperatures. These factors were all built in to the fueling maps. See revised sections 4.2.1 through 4.2.3 and 4.2.6.	4.1, 6.3
Simulation methodology	Engines and Engine Models (Sections 4.1 and 6.3)	32	Specific suggestions regarding models that need more detailed coverage: In cases where engine models have been used to generated maps, how was combustion modeled? For instance, discussion is made as to the heat transfer effect resulting from surface to volume changes connected to downsizing. More detail on the heat transfer assumptions that go into the applied heat transfer factor would be helpful. Was heat transfer modeled based on Woschni's correlation? What about friction scaling with piston speed? This would change with stroke at a constant RPM. Also friction would change with the number of bearings and cylinders.	The fueling maps were adjusted to account for the number of cylinders and the per-cylinder displacement. Detailed combustion models were not within the scope of the study; the fueling maps were based on experimental data and experience with the incorporated technologies.	4.1, 6.3

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Advanced Valvetrains (Section 4.1.1)	56	The report states that advanced valvetrain systems improve fuel consumption and GHG emissions mainly by improving engine breathing. Other benefits cited are in supporting engine downsizing and faster aftertreatment warm-up. Beyond improving volumetric efficiency and reducing pumping losses, advanced valvetrains can enable compression ratio variation to increase fuel economy and avoid knock, alter the combustion process by modulating trapped residual, and enable cylinder deactivation to reduce pumping losses. From the report, it is not clear which of the possible benefits of the advanced valvetrain packages have been harnessed in each case. A more systematic analysis of technology package combinations is warranted as several are synergistic but not additive.	The discussion in section 4.2.6.1 indicates the improvements expected in the fueling map from use of a CPS system in the 2020-2025 timeframe versus the current valvetrain. The other possible benefits of advanced valvetrains noted by this reviewer were not included in the final report, as Ricardo, based on its experience, believes these are less important characteristics than the elements included in the report.	4.1.1
Simulation methodology	Section 4.1.1 Advanced Valvetrains	82	There is no explanation of how CPS and DVA systems were modeled. There was only a description of what CPS and DVA is.	See revised section 4.1.1.	4.1.1
Inputs and Parameters	Advanced Valvetrains (Section 4.1.1)	318	Two types of advanced valvetrains were included in the study, cam-profile switching and digital valve actuation. Both of these technologies are aimed at reducing pumping losses at part-load. The impact of these technologies is difficult to predict using simplified modeling techniques and typically require consideration of compressible flow and a 1-D analysis at a minimum. Even with an appropriate fidelity model, these systems require significant amounts of optimization in order to determine the best possible performance across the torque-speed plane of the engine. It is unclear how these systems were used to generate accurate engine maps given the level of detail provided in the report.	The final report shows how and where cam-profile switching and digital valve actuation improve the fueling map. See the additional material in Section 4.1.1, including new figures to help show the physical approach and provide a range of improvement.	4.1.1
Recommendations	Advanced Valvetrains (Section 4.1.1)	319	Describe how variable valve timing technologies were applied to the base engine maps.	See response to Comment Excerpt 318.	4.1.1

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	Advanced Valvetrains (Section 4.1.1)	320	Describe the process of determining the extent of the efficiency improvement.	See response to Comment Excerpt 318.	4.1.1
Recommendations	Advanced Valvetrains (Section 4.1.1)	321	Describe how optimal valve timing was determined across the variety of engines simulated.	See response to Comment Excerpt 318.	4.1.1
Completeness	Section 4.1.2 DI Fuel Systems	131	No discussion of DI control strategy. How was it selected? Was there a separate optimization of DI control or was it one size fits all?	DI controls were not modeled. See revised sections 4.1.1 and 4.1.2.	4.1.1, 4.1.2
Inputs and Parameters		21	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: Any published fuel economy maps, or other related data, with actual numbers. For proprietary maps and data, a normalized representation would be useful, as well, without the actual bsfc values shown on the map.	To address this concern, the final report uses public fueling maps concepts, and then illustrates the technical transformation of baseline technologies to the future. See especially revised Sections 4.1 and revised Section 4.2. New Section 4.2.6 provides case studies for EGR DI Turbo and Atkinson engines. The hybrid sections (especially section 6.8) are significantly expanded as well.	4.1.1, 4.2, 4.2.6
Inputs and Parameters		24	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: Details of EGR modeling parameters, such as maps showing percentage of EGR being used at various loads.	To address this concern, the final report uses public fueling maps concepts, and then illustrates the technical transformation of baseline technologies to the future. See especially revised Sections 4.1 and revised Section 4.2. New Section 4.2.6 provides case studies for EGR DI Turbo and Atkinson engines.	4.1.1, 4.2, 4.2.6

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Engine Models	255	The report states that engines used in the model were developed using two main methods (page 14). 1. The first method assumed that "reported performance of current research engines" would closely resemble production engines of the 2020-2025 timeframe. 2. The second method began with current production engines and then a "pathway of technology improvements over the new 10-15 years that would lead to an appropriate engine configuration for the 2020-2025 timeframe" was applied. Both of these approaches are reasonable if: 1. Appropriate references are provided, 2. The reported performances for the research engines used are documented in the report, 3. The technology improvements are documented in the report, and 4. The methodology of incorporating the improvements is fully documented.	To address this concern, the final report uses public fueling maps concepts, and then illustrates the technical walk to the future. See revised Section 4.1.1 and revised Section 4.2. New Section 4.2.6 provides case studies for EGR DI Turbo and Atkinson engines. Additional references have also been provided.	4.1.1, 4.2, and 4.2.6
Inputs and Parameters	Engine Models	308	The report outlines two methods were used to produce engine models. The first method was used for boosted engines and relied upon published data on advanced concept engines which would represent production engines in the 2020-2025 timeframe. The second method was used with Atkinson and diesel engines and somehow extrapolated from current production engines to the 2020-2025 time frame. The description of both of these methods in the report is unsatisfactory. It also fails to address how the various technologies are used to build up to a single engine map for a specific powertrain. Validation, to the extent possible with future technologies, is also lacking in this area.	To address this concern, the final report uses public fueling maps concepts, and then illustrates the technical walk to the future. See revised Section 4.1.1 and revised Section 4.2. New Section 4.2.6 provides case studies for EGR DI Turbo and Atkinson engines.	4.1.1, 4.2, and 4.2.6

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Inputs and Parameters	Section 4.1.1.1 CPS	65	How were the profiles selected? Was there an optimization process for each engine size of a given engine type?	See the revisions to sections 4.1.1.1 and 4.1.1.2 generally. Section 4.2.6 provides detail on the fuel map development, and section 6.3 addresses the engine models specifically. The questions raised in this comment are not appropriate to answer by adding text to section 4.1.1.1.	4.1.1.1
Inputs and Parameters	Section 4.1.1.2 DVA	66	Was the actuation power requirement accounted for? What were the timing/lift profiles and what control strategy was used to select the timing/lift profile? Was this an active model or was the timing/lift profile preset and then unchangeable. I would expect that as the engine size changes and the boost changes the timing/lift profile will have to change with it.	See the revisions to sections 4.1.1.1 and 4.1.1.2 generally. Section 4.2.6 provides detail on the fuel map development, and section 6.3 addresses the engine models specifically. Ricardo to add to report that losses are accounted for in Figure 4.4.	4.1.1.2
Inputs and Parameters	Direct Injection Fuel Systems	322	Because of the availability of research and production data in this area, it is expected that performance from this technology was used to predict performance rather than any type of modeling approach. That being said, the report does not describe where or how this data might have been used to develop the fuel consumption map of the engines simulated nor what data sources were used.	The approach to this is similar to the approach taken to the similar comment made in Row 16. See revisions to section 4.1.2 for this comment.	4.1.2
Inputs and Parameters	Section 4.1.3 Boosting Systems	67	What about superchargers? Eaton's AMS supercharger systems offer high efficiency supercharges that are comparable to turbo's and don't have the lag problem.	The selection was based on Ricardo subject matter expert judgment for this study. The series-sequential turbocharger was used for the modeling of all boosted engines. Section 4.1.3 details the boosting system assumptions.	4.1.3
Completeness	Section 4.1.3 Boosting Systems	132	It says that other boosting systems were included in the study, but only turbocharging is discussed.	Other boosting systems were included in the study but turbocharging was the only boosting system chosen for modeling.	4.1.3

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Engine technology selection	172	The feasibility of the following assumptions for the engines modeled should be re-examined as indicated below: Turbocharger delays of the magnitude assumed in the model will result in significant driveability issues for engines that are downsized approximately 50%. Although Ricardo assumed a turbocharger delay of approximately 1.5 seconds, the comparable delay published for a research engine was significantly longer at 2.5 seconds (Lumsden et al., 2009).	See revised section 4.1.3.	4.1.3
Other Comments	Boosting Systems	272	The report states that "various boosting approaches are possible, such as superchargers, turbochargers, and electric motor-driven compressors and turbines." (page 13). However, elsewhere the report states "series-sequential turbochargers" will be used on the Stoichiometric DI Turbo engine (page 15).	The series-sequential turbocharger was used for the modeling of all boosted engines. Section 4.1.3 details the boosting system assumptions.	4.1.3
Other Comments	Boosting Systems	273	It is not clear in the report how the series-sequential turbocharger was selected from the variety of boosting devices that were introduced. Models for the turbochargers with compressor and turbine efficiency maps were not provided, so the appropriateness of these model cannot be assessed.	The selection was based on Ricardo subject matter expert judgment for this study. The series-sequential turbocharger was used for the modeling of all boosted engines. Section 4.1.3 details the boosting system assumptions.	4.1.3
Other Comments	Boosting Systems	274	Comment: The model should include a single turbocharger system with less extreme downsizing as advocated by the Sabre Engine (Coltman et al., 2008; Turner et al., 2009) as a lower cost alternative to series-sequential turbochargers.	The selection was based on Ricardo subject matter expert judgment for this study. The series-sequential turbocharger was used for the modeling of all boosted engines. Section 4.1.3 details the boosting system assumptions. EPA affirmed the recommendation of series-sequential turbos.	4.1.3
Other Comments	Stoichiometric DI Turbo Engine	280	The foregoing table indicates several significant issues: 2. The turbocharger response time for the Mahle engine is 2.5 seconds, whereas Ricardo assumed a time constant of 1.5 seconds. Such turbocharger delays are expected to result in significant driveability issues for engines that are downsized approximately 50%. (see Exhibit 7)	See revised section 4.1.3.	4.1.3

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Inputs and Parameters	Boosting System (4.1.3 and 6.3)	326	Boosting was applied to many of the different powertrain packages simulated. Beyond stating what maximum BMEP that was achievable, very little is mentioned in how the efficiency of the boosted engines were determined. Among other factors, boosting often creates a need for spark retard which costs efficiency if compression ratio is fixed. These complex issues are tied to combustion which is inherently difficulty to model. This aspect of the engine model is not well documented in the report.	The final report includes additional detail related to boosting. See revisions in 4.1.3, 4.2, 4.2.1, 4.2.6, and 6.3.	4.1.3, 4.2, 4.2.1, 4.2.6, 6.3
Other Comments	Stoichiometric DI Turbo Engine	283	Turner et al. (2009) indicates that the Sabre engine with a single stage turbocharger provides an attractive alternative to extreme downsizing with series-sequential turbochargers.	The selection was based on Ricardo subject matter expert judgment for this study. The series-sequential turbocharger was used for the modeling of all boosted engines. Section 4.1.3 details the boosting system assumptions.	4.1.3, 4.2.1
Simulation methodology	Turbocharger systems (Section 4.1.3)	33	Specific suggestions regarding models that need more detailed coverage: There is no discussion of turbocharger efficiencies and their range. Did the simulations assume current boosting technologies? Were maps used for this simulation or some other representation? Was scaling used? What were the allowed boost levels?	Turbocompressor system effects are built into the torque curve fueling map, so that the specifics of efficiency, boost P, etc. are not relevant to model. The final report includes a figure based on a relevant, published GM study, and more detailed discussion on this issue.	4.1.3, 4.2.1, 6.3

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Boosting System (4.1.3 and 6.3)	57	A two-stage system is indeed promising for advanced turbocharging concepts. A distinction should be made between series and sequential configurations. Air flow manipulation can make it a series system (two-stage expansion and compression) or a sequential system (turbos activated at different rpm). Variable geometry or twin-scroll turbines can be good options for the low or high pressure stages, respectively. A two-stage turbocharging system like this would take advantage of the lean SI exhaust enthalpy, reduce pumping work (or even aid pumping), avoid mechanical work penalties, improve engine transient response, enable high dilution levels (if desired) and probably help keep in-cylinder compression ratio below 12:1, since significant compression would be done before the cylinder. EGR flow could be driven through a low pressure loop (after the turbines) or an intermediate pressure loop (between the turbines). The resulting turbo lag will depend on the details of the configuration and the control logic used. Note that the assumption of a time constant of 1.5 seconds (as stated in the report) to represent the expected delay may not hold true in all cases.	Sections 4.1.3, 4.2.6, 6.2, and 6.3 provide additional discussion and graphics related to turbo lag and the two-stage system concept and how it was applied in this study.	4.1.3, 4.2.6, 6.2, 6.3
Inputs and Parameters		22	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: Baseline maps used to represent turbomachinery, in actual or normalized form.	See figures and text added to the final report, including section 4.1.3 and 4.2.6.1.	4.1.3, 4.2.6.1
Recommendations	Boosting System (4.1.3 and 6.3)	327	Describe the process of arriving at the boosted engine maps.	The final report includes additional detail related to boosting. See revisions in 4.1.3, 4.2, 4.2.1, 4.2.6, and 6.3.	4.1.3, 6.3
Recommendations	Boosting System (4.1.3 and 6.3)	328	Describe how factors like knock are addressed in the creation of these maps.	The engine knock strategy itself was assumed to be similar to today's methods. The fueling maps reflect the effect of knock mitigation strategies.	4.1.3, 6.3
Inputs and Parameters	Turbo Lag	391	The data and methods used in modeling turbo lag are appropriate and there is sufficient explanation and data to support the model.	EPA and Ricardo appreciate the comment; no further response is required.	4.1.3, 6.3

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		403	Engine Model: The trend in engine technology is forced induction (engine downsizing). I think the selection of turbo only is too limiting. I anticipate variable speed supercharging and other combination of forced induction. I think the study would do well to include this.	The selection was based on Ricardo subject matter expert judgment for this study. The series-sequential turbocharger was used for the modeling of all boosted engines. Section 4.1.3 details the boosting system assumptions.	4.1.3, 6.3
Inputs and Parameters		406	Diesel Technology: Curious about the author's comment regarding supercharging, "advances to avoid variable speed". Why not variable speed?	See response to Comment Excerpt 403.	4.1.3, 6.3
Inputs and Parameters	Section 4.1.4 Other Engine Technologies	68	regarding global engine friction reduction, what value(s) was assigned to that? Was it the same across all engines? If so, why?	Friction reduction improvements were assumed to be 3.5% across all engine maps, and were extrapolated from the benefits assumed in the 2008 EPA study for 2012-2016. (see section 4.2.6.1)	4.1.4
Inputs and Parameters		69	How was the FEAD electrification energy balance accomplished? Was additional load placed on the alternator?	The load of the electrical cooling fan is included in the base electrical loads. Mechanical fans are included in the engine map.	4.1.4, 6.3.2
Inputs and Parameters	Section 4.2 Engine Configurations	71	Quantification needed …"The combinations of technologies encompassed in each advanced engine concept provide benefits to the fueling map…."	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them.	4.2

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology	Engines and Engine Models (Sections 4.1 and 6.3)	30	Specific suggestions regarding models that need more detailed coverage: It is not clear whether the engine maps in the simulation tool were generated based on simulations or existing experimental data, somehow fitted and scaled to the various configurations. In general, the explanation on how maps were obtained is vague for such an important component. In one section, the report states that the fueling maps and other engine model parameters used in the study were based on published data. If so, it would be nice to have a list of the published materials that have been used as the resource. In Section 4.2, the report states that the performance of the engines in 2020-25 were developed by taking the current research engines and assuming the performance of the 2020 production engines will match that of the research engine under consideration. Does this assumption take into account the emission standards in 2020, and do the current research engines match those emission standards? What is the systematic methodology that has been adopted to scale the performance and fuel economy of current baseline engines to engine models for 2020-25? Also, the report lacks detail concerning the methodology of extrapolating from available maps to maps reflecting the effects on overall engine performance of the combination of the future technologies considered.	The final report adds text on criteria pollutant standards to confirm that the study assumed LEVIII=SULEV II. The diesel engines fueling maps account for these standards. The final report includes more description on the methodology, and explains how the referenced publications inform the model. See revised sections 4.2, 4.2.5 and 4.2.6.	4.2, 4.2.5, 4.2.6
Other Comments	Engine Models	254	Engine models provided the torque curve, fueling map and other input parameters (which were not specified in the report) (page 25). Since the report stated that "The fueling maps and other engine model parameters used in the study were based on published data and Ricardo proprietary data" (page 26), their adequacy and suitability could not be assessed.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them.	4.2, 6.3

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Engine Models	260	In summary, the Ricardo report provided insufficient descriptions of the derivation of the maps used for all of the engines in this study, which included: - Baseline - Stoichiometric DI Turbo - Lean-Stoichiometric Switching - EGR DI Turbo - Atkinson Cycle - Advanced Diesel	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them.	4.2, 6.3
Recommendations	Engine Models	310	Provide fuel and efficiency map data for all engines used in simulation.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of the modeling and related issues, and how the study addressed them.	4.2, 6.3
Recommendations	Engine Models	312	Provide specific references of which published data was used to predict performance of the future engines. Some references are given, however, it is not clear how exactly these references are used.	Multiple public references were provided. These were used by the study group to balance and verify the final engine maps based on Ricardo research engine data.	4.2, 6.3
Recommendations	Engine Models	313	Wherever possible, provide validation against data on similar technologies.	Please refer to the revised report concerning technology/model validation.	4.2, 6.3
Recommendations	Engine Models	314	Describe in detail the approach used to “stack up” technologies for a given powertrain recipe.	This is inherent to Ricardo's proprietary vehicle models.	4.2, 6.3
Recommendations	Engine technology selection	343	Describe in greater detail the approach used to model technology stack-up on the advanced vehicles.	This is inherent to Ricardo's proprietary vehicle models.	4.2, 6.3
Recommendations	Engine technology selection	344	Provide some form of validation that this approach is justified.	Engineering judgment was used by Ricardo, EPA, and the advisory committee to select engines suitable for the various vehicle classes.	4.2, 6.3

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology	Section 4.2.1 Stoich DI Turbo	83	Quantify how did the cooled exhaust manifold/lower turbine inlet temp improved the BSFC map. This is a good example of technology interaction…how did the radiator size grow to accommodate the additional heat rejection; how did the frontal area of the vehicle change to accommodate the larger radiator?	See Figure 4.6 for zone of engine operation where enrichment for in-cylinder cooling was removed. The effect on fuel economy results is modest, since the Stoichiometric DI Turbo engine only has a few operating points in this range over the US06 cycle. It was assumed that specific heat rejection issues from the application of advanced technologies would be addressed without affecting fuel economy within the design space considered, for example, within the range of vehicle mass and frontal area and aerodynamic drag.	4.2.1
Inputs and Parameters	Engine technology selection	171	The feasibility of the following assumptions for the engines modeled should be re-examined as indicated below: None of the Stoichiometric DI Turbo engines listed as references by Ricardo limited the turbine inlet temperature to a value as low as the 950C limit in the Ricardo model (Coltman et al., 2008; Turner et al., 2009; Lumsden et al., 2009). Reducing the turbine inlet temperature to reach this limit is expected to result in BMEP levels below the assumed 25-30 bar level in the model (which were obtained in the referenced engine with a turbine inlet temperature of 1025C).	See revisions in section 4.2.1 of the final report, including addition of Schmuck-Soldan et al. (2011) reference. Water-cooled exhaust manifolds were a technology considered in the establishing of the 950C limit. Ricardo's SME's made adjustments to the map in GT/Power to account for the 950C constraint that EPA asked them to incorporate.	4.2.1
Other Comments	Stoichiometric DI Turbo Engine	275	The table below compares several attributes of the Ricardo Stoichiometric DI Turbo Engine with the Mahle Turbocharged, DI Concept Engine. (See Exhibit 7)	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	4.2.1
Other Comments	Stoichiometric DI Turbo Engine	276	Key content of the Mahle Turbocharged, DI Concept Engine: - Two turbochargers in series - Charge air cooler - Dual variable valve timing - High energy ignition coils - Fabricated, sodium cooled valves - EGR cooler	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	4.2.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Stoichiometric DI Turbo Engine	277	Lumsden et al. (2009) describing the Mahle concept engine stated that lowest fuel consumption that usually occurs around 2000 rpm had moved out to 4000 rpm for the series-sequential turbocharged engine.	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	4.2.1
Other Comments	Stoichiometric DI Turbo Engine	279	The foregoing table indicates several significant issues: 1. The turbine inlet temperature of the Mahle engine is significantly higher than the limit assumed for the Ricardo engine (1025C vs. 950C). Reducing the turbine inlet temperature is expected to result in lower BMEP levels where the temperature is limited. (see Exhibit 7)	It is not possible for an apples-to-apples comparison of today's Mahle engine vs. the 2020 advanced engines. Too many factors, such as turbocharger efficiency can change BMEP levels for a given turbine inlet temperature.	4.2.1
Other Comments	Stoichiometric DI Turbo Engine	281	The table below compares several attributes of the Ricardo Stoichiometric DI Turbo Engine with the Lotus Sabre Engine. (see Exhibit 8)	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	4.2.1
Other Comments	Stoichiometric DI Turbo Engine	282	The paper on the Sabre engine (Turner et al., 2009) indicates that operation at lower turbine inlet temperatures results in a reduction in BMEP. However, the turbine inlet temperature for the Sabre engine is still 40C above Ricardo's assumption.	See excerpt 279	4.2.1
Other Comments	Cooled Exhaust Manifold	284	The Ricardo report states, "The future engine configuration was assumed to use a cooled exhaust manifold to keep the turbine inlet temperature below 950C…" No explanation was provided of how the limit on turbine inlet temperature would affect boost pressure and power.	The limit on turbo inlet temperature was chosen to avoid prohibitively expensive turbochargers and is accounted for in the model.	4.2.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
References Used	References (Used for this Review that are also listed in the Report)	292	References used to establish the basis for the Stoichiometric DI Turbo engine assumptions (page 15 of the report): 1. Coltman, et al. (2008), "Project Sabre: A Close-Spaced Direct Injection 3-Cylinder Engine with Synergistic Technologies to Achieve Low CO2 Output", SAE Paper 2008-01-0138 2. Turner, et al. (2009), 'Sabre: A Cost-Effective Engine Technology Combination for High Efficiency, High Performance and Low CO2 Emissions", IMechE conference proceedings 3 Lumsden, et al. (2009), "Development of a Turbocharged Direct Injection Downsizing Demonstrator Engine", SAE Paper 2009-01-1503	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	4.2.1
Recommendations	BSFC Map Comparisons	396	I reviewed this but do not have any substantive comments. All of the figures compare pseudo-virtual engines with other pseudo-virtual engines. A comparison back to a known, experimentally validated engine current engine would have been more useful for me as it would allow one to see the magnitude of improvements that were assumed for the 2020 engines and where on the map these improvements were made.	Please refer to Coltman et al. (2008) and Turner et al. (2009) for publically disclosed engine examples for comparison.	4.2.1
Recommendations	Direct Injection Fuel Systems	323	Cite sources of data used to predict DI performance.	Predictions were based on Ricardo experience with research and production engines much of which is proprietary.	4.2.1, 4.2.6
Recommendations	Direct Injection Fuel Systems	324	Describe how this data was used to develop the future engine performance maps.	See response to Comment Excerpt 323.	4.2.1, 4.2.6
Recommendations	Direct Injection Fuel Systems	325	Provide validation of modeling techniques used.	See response to Comment Excerpt 323.	4.2.1, 4.2.6
Other Comments	Stoichiometric DI Turbo Engine	278	Issue: The Ricardo report did not discuss the concern that the lowest fuel consumption in a series-sequential turbocharged engine had moved out to 4000 rpm, rather than the usual 2000 rpm and did not discuss how this concern was handled.	This is true of the referenced material but not in the study. See significant revisions to section 4.2.1 and addition of 4.2.6.1.	4.2.1, 4.2.6.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Lean-Stoichiometric Switching (Section 4.2.2)	58	The mixed-mode operation considered in the report seems to switch between stoichiometric and lean SI direct injection operation. There are several multi-mode combustion efforts under development that encompass several more combustion modes, including HCCI and Spark assisted compression ignition with amounts of EGR dilution.	EPA and Ricardo appreciate the comment. Future analyses could expand the scope to include these technologies.	4.2.2
Simulation methodology	Section 4.2.2 Lean Stoich Switching	84	This type of tech points to one of the dangers of optimizing configuration/technology/control strategy to the drive cycles; that is that it has the potential to over constrain the design and effect the "real world" performance/fuel economy.	EPA and Ricardo appreciate the comment; no further response is required.	4.2.2
Other Comments	Lean-Stoichiometric Switching Engine	288	The report states that this engine will use a lean NOx trap or a urea-based SCR system (page 15). The use of fuel as a reducing agent was also suggested in the report (page 16). However, the fuel economy penalty associated with regenerating the NOx trap or the reducing agent for the SCR system was not provided.	The fuel penalty varies with vehicle class and other factors and is accounted for in the Ricardo proprietary model.	4.2.2

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Aftertreatment/ Emissions Solutions	315	Based on the report, it seems that emissions solutions are assumed to be available for all powertrain technology packages selected. The report discusses this in some qualitative detail in section 4.2.2 with respect to lean-stoichiometric switching. This discussion is somewhat incomplete, in that the way it is written it assumes operating at stoichiometry lowers exhaust gas temperature. In reality, switching from lean to stoichiometric operation at constant load results in higher exhaust gas temperatures. Despite this factual inconsistency, it is indeed generally better to operate a temperature sensitive catalyst hot and stoichiometric or rich rather than hot and lean – so the concept of lean-stoich switching is valid even if the explanation provided is not. Even without this factual inconsistency, some additional discussion of aftertreatment systems would be of benefit given that lean-burn gasoline engines are at present a well-known technology for many years that is still problematic with respect to emissions control. A separate issue is the topic of fuel enrichment for exhaust temperature management which will have an important impact on emissions and, if emissions are excessive, reduce the peak torque available from an engine.	The lean-stoich switching points were determined to maintain exhaust temperatures and catalyst operating limits. See revised section 4.2.2.	4.2.2
Simulation methodology	Section 4.2.5 Advanced Diesel	86	Why were only the benefits of improved pumping losses or friction considered? What improvements were assigned to these benefits? Was it across the board or regional? What about advanced boosting technology for these engines?	Friction and pumping losses are the primary targets to increase the efficiency of the engine. Advanced boosting technology includes two-stage turbocharging for the advanced turbo engines. In addition, combustion advancements (such as the lean boost engine) further lower fuel consumption.	4.2.5

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology		87	Ricardo's expectation for pace and direction: I thought there was an advisory committee making these decisions. I'm surprised that they think boost will be limited to 17-23bar.	The Advisory Committee and EPA provided input on many elements of the study, working with Ricardo's expertise and experience. The final study retains this language as a reasonable expectation for advanced diesel technologies in the study timeframe. The final boost limit was raised to 27 bar.	4.2.5
Other Comments	Engine Models	257	The description of the derivation of the engine models in the report was, at best, vague, as illustrated by the two examples below: Example 2: Advanced Diesel For the advanced diesel, the report provided the following description: "…the LHDT engine torque curve and fueling maps were generated by starting with a 6.6L diesel engine typical for this class and applying the benefits of improvements in pumping losses or friction to the fueling map". No description of the improvements in pumping losses or friction reduction was provided and the variation of these improvements over the speed and load map were not provided. In addition, the baseline 6.6L engine map was not provided, the 6.6L friction map was not provided and the methodology for applying the improvements to the 6.6L engine map was not provided.	As described in Section 4.2, the Diesel engines and Atkinson engines used the same methodology to translate current production fueling maps to the 2020–2025 timeframe. This methodology is described in detail in Section 4.2.6.2, with the example of an Atkinson engine since a published map can be presented as a starting point. The Diesel engine maps were based on Ricardo Confidential Business Information.	4.2.5
Inputs and Parameters	Input Data Review	397	The documentation on the Diesel engine maps was helpful; however, it did not discuss how the 2020 engine maps were developed. This is critical for having confidence in the predictions made for the Diesel powertrains in 2020.	See Section 4.2.5.	4.2.5
Inputs and Parameters		405	Diesel Engine Fuel Maps: The presentation shows the technologies to be deployed, but doesn't discuss how the 2020 bsfc maps were arrived at. It might be helpful to also use the same method for comparison that the authors used to show LBDI vs EGR.	See Section 4.2.5.	4.2.5

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology	Section 4.2.4 Atkinson Cycle	85	How do the 2020-2025 maps differ from the 2010 maps?	See new section 4.2.6.	4.2.6
Inputs and Parameters		408	EBDI Engine: Couldn't find fuel economy benefit discussion in presentation. Should be done as gasoline or energy equivalent. I know CO2 is proportional, but….	EBDI results shown are for "E0" fuel.	4.2.6.1
Simulation methodology	6.3 Engine Models	92	Two methods to develop engine models were discussed. It is not disclosed which approach was used for which engine. I recommend that one approach be developed for all engines or both approaches be applied to each engine to converge to a solution.	EPA and the program team did not opt for this approach in designing this study. The final report provides further detail on the different approaches (see 6.3 plus a number of revisions in section 4.2, especially 4.2.6.a and 4.2.6.2). The option used was recommended by Ricardo and intended to be an appropriate approach given the current data available (in some cases a research engine was used because it provided an appropriate starting point, while in other cases a current production engine was determined to be the most appropriate starting point).	4.2.6.1, 4.2.6.2, 6.3
References Used	References (Used for this Review that are also listed in the Report)	294	References containing supporting information for the hybrid powertrains: 5. Hellenbroich, et al. (2009), "FEV's New Parallel Hybrid Transmission with Single Dry Clutch and Electric Torque Support" 6. Staunton, et al. (2006), "Evaluation of 2004 Toyota Prius Hybrid Electric Drive System", ORNL technical report TM-2006/423	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	4.3
Completeness	Section 4.3.1 Micro Hybrids	134	It is implied that electrified accessories aren't used in this configuration. I don't see that as the case.	This case includes electrified accessories, but assumes no electrified cooling. See Weissier article cited in revised report on recent expectations for addressing cooling needs.	4.3.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Accessory load assumptions	185	The accessory selections listed in Table 5-2 (page 22) appear to be adequate except for the following issue: Belt driven air conditioning for the stop-start powertrain configuration is not acceptable for driver comfort. Electrically driven air conditioning is required for the stop-start powertrain configuration to provide driver comfort for extended idle periods.	The study runs assumed belt-driven for this situation. Also see Weissier article cited in revised report on recent expectations for addressing cooling needs. EPA and Ricardo will consider this issue for future analysis.	4.3.1
Inputs and Parameters	Accessory load assumptions	189	Recommendation: Both mechanically driven and electrically driven accessory power requirements should be clearly provided in the report.	See accessory power requirements table.	4.3.1, 6.3.2
Other Comments	P2 Parallel Hybrid (Section 4.3.2)	59	P2 refers to pre-transmission parallel hybrid, where an electric machine is placed in between the engine and the transmission. While the report does not discuss details, there are two possible configurations: (i) a single clutch, located in between the engine and the electric machine, such as in the Hyundai Sonata, and (ii) two clutches, one in between the engine and the motor, and the other one in between the motor and the transmission, such as in the Infiniti M35 HEV. The P2 system looks promising to achieve good efficiency, but remaining barriers include cost, drive quality, durability and to a lesser extend packaging. Careful consideration of details is needed to properly assess benefits compared to a single mode power split. Early reports have indicated that Nissan got 38% mpg increase out of their P2 and Hyundai got 42%, both with higher horsepower, as well. However, the P2 Touareg doesn't seem to meet EPA 2012 CAFE standards.	EPA and Ricardo appreciate the comment; no further response is required.	4.3.2
Completeness	Section 4.3.2 P2 Hybrid	135	No discussion of why DCT was only transmission used for P2 hybrids instead of CVT and AMT.	DCTs were chosen as current industry direction and to simplify the study scope while modeling a representative technology.	4.3.2
Other Comments	Transmission Technologies (Section 4.4)	60	What about automatic transmissions with automated clutch replacing the torque convertor and lock-up clutch? This is also a possibility.	This technology was not part of the study. EPA and Ricardo appreciate the comment; no further response is required.	4.4

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness	4.4 Transmission Technologies	136	What types of CVT's were in the original mix? Toroidals, push-belts, Miller?	CVTs were not part of this study. See edits to section 4.4.	4.4
Inputs and Parameters	Transmission technology selection	173	The transmission technologies selected for this study, listed in Table 5.3 (page 23) are appropriate.	EPA and Ricardo appreciate the comment; no further response is required.	4.4, 5.2
Inputs and Parameters	6.4 Transmission Models	76	no efficiency maps, no description of the efficiency maps. What was efficiency a function of? Typically it's gear ratio, torque and speed.	Efficiency assumptions added to report. See revised section 4.4 and 6.4.	4.4, 6.4
Simulation methodology	4.4 Transmission Technologies	88	How were the gear ratios selected? What about shift logic?	Gear ratios added to report and shift logic detailed in section 6.4 of the final report.	4.4, 6.4
Inputs and Parameters	Transmission technology selection	175	The report mentions that the transmissions include dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants (page 22).	See revisions to section 4.4 and 6.4 in the final report.	4.4, 6.4

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Transmission Models	261	Similar to engine models, the description of the derivation of transmission models was also vague. Using the automatic transmission model as an example, "For the 2020-2025 timeframe, losses in automatic transmissions are expected to be about 20-33% lower than in current automatic transmissions from the specific technologies described below." The specific technologies that could provide these reductions appeared to include: - Shift clutch technology - to improve thermal capacity of the shifting clutch to reduce plate count and lower clutch losses during shifting. - Improved kinematic design – no description of these improvements was provided. - Dry sump – to reduce windage and churning losses. - Efficient components – improvements in seals, bearings and clutches to reduce drag. - Super finishing - improvements expected were not specified. - Lubrication- new developments in base oils and additive packages, but improvements were not specified.	In-house efficiency calculations provided the overall average transmission efficiencies based on benchmarking data, with small adjustments based on the expected improvements of advanced technologies.	4.4, 6.4

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Transmission Models	262	In addition to not specifying the improvements expected from these technologies, no indication was provided of how these technologies were applied to the transmission models. For example, - The report stated that losses in automatic transmissions are expected to be about 20-33% lower than in current automatic transmissions (page 19). However, the baseline losses were not provided for reference and the means to achieve these reductions were not described. - The report stated that energy losses in DCTs are expected to be 40-50% lower than in current automatic transmissions (page 19). The details of this reduction were not provided and references describing these reductions were not provided. - Bearing and seal losses have a greater effect on efficiency at light loads than at heavy loads. The report did not describe how these losses were incorporated in the model. In contrast to the lack of descriptions of details in the report, PQA and Ricardo (2008), as an example, provided the following map of bearing losses in a transmission as a function of shaft diameter and speed. Similar details for the relevant aspects of the transmission models in this report would have been expected. (See Exhibit 4)	Efficiency assumptions added to report. See revised section 4.4 and 6.4.	4.4, 6.4
Other Comments	Transmission Models	263	In summary, the Ricardo report provided insufficient descriptions of the derivation of the maps for the following transmissions: - Advanced automatic - Dry clutch DCT - Wet clutch DCT - P2 Parallel hybrid transmission - PS Power Split hybrid transmission	The transmission model only captures efficiency and torque/speed for each gear. Transmission efficiency for each gear was derived from actual component test data and normalized to represent a "typical" transmission.	4.4, 6.4
Other Comments	Transmission Models	264	In addition, the models for the automatic transmissions of the baseline vehicles were not provided, so that their adequacy could not be assessed.	The transmission model only captures efficiency and torque/speed for each gear.	4.4, 6.4

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Transmissions	360	This peer reviewer is not as well-practiced in transmissions as in other areas in this review. Because of this, a more limited review was conducted of this aspect of the report. As with the other areas of the report, the general concern in this area is the inadequacy of documentation of the modeling approach and validation.	See revisions to section 4.4 and 6.4 in the final report.	4.4, 6.4
Recommendations	Transmissions	361	Cite data sources used in modeling.	See revised Sections 4.4, 6.4 (gearbox), and 6.5 (lock-up). Includes Figure 4.9.	4.4, 6.4, 6.5
Recommendations	Transmissions	362	Validate models wherever possible.	See revised Sections 4.4, 6.4 (gearbox), and 6.5 (lock-up). Includes Figure 4.9.	4.4, 6.4, 6.5
Recommendations	Transmissions	363	Fully describe transmission models/maps and processes used to generate them.	See revised Sections 4.4, 6.4 (gearbox), and 6.5 (lock-up). Includes Figure 4.9.	4.4, 6.4, 6.5
Recommendations	Transmissions	364	Fully describe clutch/torque converter models/maps and processes used to generate them.	See revised Sections 4.4, 6.4 (gearbox), and 6.5 (lock-up). Includes Figure 4.9.	4.4, 6.4, 6.5
Recommendations	Transmissions	365	Fully describe the process used to generate shift maps and the operation of the shift controller.	See revised Sections 4.4, 6.4 (gearbox), and 6.5 (lock-up). Includes Figure 4.9.	4.4, 6.4, 6.5
Recommendations	Transmissions	366	Fully describe the lockup controller (i.e. how soon can it enter lockup after shifting?).	See revised Sections 4.4, 6.4 (gearbox), and 6.5 (lock-up). Includes Figure 4.9.	4.4, 6.4, 6.5
Recommendations	Transmissions	367	Fully describe the process for modeling torque holes during shifting.	See revised Sections 4.4, 6.4 (gearbox), and 6.5 (lock-up). Includes Figure 4.9.	4.4, 6.4, 6.5
Recommendations	Transmissions	368	Fully describe the model used for the final drive (i.e. inputs/structure/outputs).	See revised Sections 4.4, 6.4 (gearbox), and 6.5 (lock-up). Includes Figure 4.9.	4.4, 6.4, 6.5

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness	4.4.1 Automatic Transmission	138	No logical explanation for the 20-33% improvement…how was this number arrived at?	Reference is made to loss reductions (88% efficient trans has 12% loss). Efficiency goes from approximately 88% to 90.5-92% (varies by gear). Improvements considered by committee and trans experts included reducing number clutch plates, reducing rotating speed differences between components, dry sump, improved lockup clutch dampers, superfinishing, lubricants, seals and bearings. The processes to achieve these improvements were discussed by the technology committee and are proprietary. Also, an improved efficiency torque converter was assumed by EPA based on their discussions with suppliers. The ZF 8HP trans that is scheduled for the 2012 Chrysler already has some of these design features.	4.4.1-4.4.2
Completeness	4.4.3 Wet clutch	139	It said these were expected to be heavier, cost more and be less efficient than DCT's so why where they included?	Technology selected during selection phase of the study by EPA with input from others. See full text in 4.4.3 which discusses evolution toward damp clutch systems.	4.4.3
Results	Section 4.4.6 Shifting Clutch Technology	101	"The technology will be best suited to smaller vehicle segments because of reduced drivability expectations" – not in the US market.	Disagree. Reduced drivability expectations versus shift efficiency (and improved fuel economy) will tend to exist mainly in the small vehicle segment, for the US bias toward drivability that the reviewer suggests. Luxury small cars are not considered to be representative of the class average.	4.4.6

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Results	Section 4.4.7 Improved Kinematic Design	102	Assumes a sweeping improvement without identifying a clear rationale…doesn't appear to describe a scientific or objective approach.	Section 4.4.7 could repeat the statement about reducing the number clutch plates and reducing rotating speed differences between rotating components is part of improved kinematic design. This is similar to the improvement ZF has attained in the 8HP trans for the 2012 Chrysler 300.	4.4.7
Other Comments	Efficient Components (Section 4.4.9)	61	Efficient components should also include gears since rotating gears are also a major source of drag. Designing a better profile for gear teeth can reduce drag losses.	Gears are included in 4.4.10 Super Finishing but could also be added to the component list in 4.4.9.	4.4.10
Completeness	4.4.10 Super Finishing	140	How much improvement is attributed to super finishing?	This is not attributed to separately, but as part of the suite of improvements in 4.4.6-4.4.11. See revised discussion in section 6.4.	4.4.10, 6.4
Results	Section 4.4.11 Lubrication	103	Assumes a sweeping improvement without identifying a clear rationale…doesn't appear to describe a scientific or objective approach.	Technology options were presented to EPA and Advisory Committee, and then selections made based on EPA input. This technology can apply across vehicles classes as stated in report. Improvements in transmission lubrication are based on Ricardo Confidential Business Information.	4.4.11
Simulation methodology		90	There are several types of rolling resistance models, what type was used?	Standard rolling resistance models incorporated into the MSC.Easy5 libraries were used.	4.5

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness		144	There are several types of rolling resistance models, what type was used?	As stated in Section 4.5: "Several vehicle technologies were also considered for the study to the extent that they help support future ranges of vehicle mass, aerodynamic drag, and rolling resistance for each of the vehicle classes in the study. The potential levels of improvement for these "road load reduction" technologies were not explicitly quantified; rather, they were included as independent input variables within the complex systems modeling approach."	4.5
Recommendations		158	Where lumped improvements are made, I recommend using historical results to publish technology improvement curves. For example, the parasitic losses (Cd, Crr) should be quantifiable. Vehicle mass reductions as well.	As stated in Section 4.5: "Several vehicle technologies were also considered for the study to the extent that they help support future ranges of vehicle mass, aerodynamic drag, and rolling resistance for each of the vehicle classes in the study. The potential levels of improvement for these "road load reduction" technologies were not explicitly quantified; rather, they were included as independent input variables within the complex systems modeling approach."	4.5
Simulation methodology		415	Accessories: I don't see any discussion on the treatment of accessories. I believe from my review of the previous material, that the authors assume that all accessories will be electric. I think that engine driven accessories will play a key role in 2020.	See revised section 4.5.	4.5
Completeness	4.5 Vehicle Technologies	141	No values for mass, rolling resistance or drag given. No discussion of the improvement possibilities. This would be a good place to use historical trends for vehicle mass reduction, aero improvements and parasitic loss improvement.	These were not a focal part of this study. The complex systems tool allows the user to evaluate a range of changes (on a percentage basis) for these various parameters. See new text in 4.5, and information in Section 5.2.	4.5, 5.2

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology	Intelligent Cooling Systems (Section 4.3.1)	34	Specific suggestions regarding models that need more detailed coverage: The report describes intelligent cooling systems, but does not provide any estimates of the anticipated reductions in fuel consumption over the FTP cycle, though related papers have been published in the open literature.	See revised section 4.5.1.	4.5.1
Simulation methodology	Intelligent Cooling Systems (Section 4.3.1)	35	Specific suggestions regarding models that need more detailed coverage: Sizing of various cooling components plays a very crucial role in fuel economy predictions. The report does not provide any detail on how the optimum cooling flow required for a given engine- transmission combination was determined. This would significantly affect the oil, coolant and transmission oil pump RPMs, which would in turn significantly change the accessory loads.	See revised section 4.5.1.	4.5.1
Simulation methodology	Intelligent Cooling Systems (Section 4.3.1)	36	Specific suggestions regarding models that need more detailed coverage: In addition, the report does not have any discussion on how modified cooling components (radiator, condenser, etc.) would be sized for more efficient powertrains. For instance, a more efficient engine that would reject less heat would likely need a smaller radiator and lesser airflow through the radiator; hence, the grill opening could be reduced to cut down on aero drag. A high efficiency transmission will not reject a lot of heat to the transmission oil; thus, a smaller transmission oil cooler could be used.	See revised section 4.5.1.	4.5.1
Inputs and Parameters		23	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: The baseline vehicle cooling system and accessory schematic vs. cooling system and accessory load schematics of the future engines considered in the simulation.	After reviewing the overall comments, Ricardo and EPA did not believe that adding significant detail to the cooling and other accessory load discussions in the final report would assist in the overall presentation of the study findings.	4.5.1, 6.3.2

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology	Constraints	41	Specific suggestions regarding models that need more detailed coverage: There is no discussion in the report that discusses the constraints on the combinations that can be implemented in real life. For example, would a multi-air system that is currently designed for small size engines work for a full size car?	See revised section 5.	5
Results	Issue with CSM	218	Issue: The technology "package definitions" (page 22 and 23) precluded an examination of the individual effects of a variety of technologies.	EPA and Ricardo acknowledge this limitation. As with any study, there is a need to balance the ability to evaluate each variable, with the ability to contain the study to a manageable scope.	5
Results	Other issues	220	The Advanced Diesel does not appear to be modeled for the Standard Car and Small MPV (page 46 and 47), yet no reason was provided.	Many technology combinations decided to be less popular were not modeled to constrain the scope of the study to a reasonable size while maintaining sufficient fidelity. EPA and the advisory committee precluded diesels from certain vehicle classes based on vehicle cost, and in a desire to contain the project scope.	5
Results	Other issues	221	The P2 and PS hybrid system was not modeled for the LHDT (page 47), yet no reason was provided.	Hybrids requiring towing were not considered. Many technology combinations decided to be less popular were not modeled to constrain the scope of the study to a reasonable size while maintaining sufficient fidelity. LHDT (class 3) vehicles are also not in the light duty category.	5
Recommendations		246	Recommendation: A default weight increase/decrease should be added for each technology. If weight reductions are to be studied, then the user should have to input a specific design change, with the appropriate weight reduction built into the model, rather that having an arbitrary slider for weight.	The mass of technologies was not included in this study due to the evolving nature and complex opinions regarding this topic. The user of the RSM tool is responsible to add or remove mass from the baseline vehicle to account for the mass of technologies.	5

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		1	The vehicle classes and baseline exemplars are reasonably chosen, within the constraint that vehicle size, footprint, and interior volume for each class be locked to the 2010 base year. It is likely that new vehicle classes will emerge by 2025 and/or that these "locking" restraints will be relaxed.	EPA and Ricardo appreciate the comment. Future analyses could consider modifications to the locking constraints noted by the reviewer.	5.2
Inputs and Parameters		26	The engine technology selection appears somewhat limited in terms of the selected combinations. For example, why is the Atkinson engine not boosted as well? Moreover, a variable valve actuation technology, as common and important as variable cam phasing, is not included. As already stated in the introductory comments, advanced combustion technologies, such as HCCI, are worth considering. More flexibility in the engine and vehicle parameters would also allow better understanding of the improvements obtained for individual technologies and possibly even show some potential synergies not currently identified.	The technology selections and combinations were selected to provide a representative group of combinations that reflect the thinking of the program team of some of the most common expected combinations across the range of light duty classifications. The full slate of options considered is set forth in Attachment A to the final report. While EPA agrees that additional combinations are of interest, the project scope was a significant undertaking, both in terms of budget and time, with the options selected. The report is one of the technical studies relevant to EPA's ongoing rulemaking efforts, and the scope was designed to support that effort. EPA anticipates that others and perhaps EPA will continue to explore these issues with further studies that add scope.	5.2
Results	5.2 Vehicle Configuration and technology combinations	105	Also there is no scientific or objective reason given for the DoE ranges. It appears that I can make any vehicle 60% less mass, 70% less rolling resistance etc.…This will skew the results towards that end of the DoE, when they may not be practically achievable.	See edits in section 5.2: "Tables 5.4 and 5.5 also show the ranges of the continuous parameters—expressed as a percentage of the nominal value—used in the DoE study for the conventional and hybrid powertrains, respectively. The ranges were kept purposely broad, to cover the entire span of practical powertrain design options, with some added margin to allow a full analysis of parametric trends."	5.2

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness	5.2 Vehicle Configuration and technology combinations	142	While the tables show the vehicle configurations, more discussion regarding the selection criteria for each vehicle is warranted. In some cases this discussion was attempted in the technology sections, but I don't think it should go there.	EPA believes the significant additional text and figures added to the final report sufficiently describe the vehicle configurations that were modeled as part of this study. This includes text in section 5.2, as well as expanded discussions throughout sections 4 and 6.	5.2
Inputs and Parameters	Hybrid technology selection	177	The hybrid technologies selected for this study, listed in Table 5.2 (page 22) are appropriate.	EPA and Ricardo appreciate the comment; no further response is required.	5.2
Inputs and Parameters	DOE ranges	192	The following DOE ranges for Baseline and Conventional Stop-Start (page 23) appear to be appropriate, with the exception of Engine Displacement. Since the default for the Stoichiometric DI Turbo engine appears to be greater than 50% reduction in displacement (Standard Car baseline of 2.4L is reduced to 1.04L for the Stoichiometric DI Turbo (page 46)), the opportunity should be provided to start with a displacment near the baseline engine (2.4L) and progressively decrease it to approximatly 50% (1.04L). This would require an Engine Displacement upper range of over 200%. The model should also have the capabilty of increasing the boost pressure as the displacement is reduced. (See Exhibit 1).	The reason for the 1.04L nominal displacement for the Standard Car was to keep performance metrics equal to today's model. The methodology of the study kept boost levels (and BMEP) constant with displacement change to allow for apples to apples comparison of displacement change. Furthermore, the advanced turbo engines are already running high BMEP levels.	5.2
Inputs and Parameters	DOE ranges	193	The following DOE ranges for P2 and PS hybrid vehicles (page 24) appear to be appropriate (See Exhibit 2)	EPA and Ricardo appreciate the comment; no further response is required.	5.2

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		2	The design of experiment (DoE) ranges, Tables 5.4, 5.5, 8.1, and 8.2, are reasonable and do not exclude likely sizings. The assumed alternator baseline and advanced alternator efficiencies are reasonable. The assumed reduction in automatic transmission losses is reasonable, but not aggressive for 15 development years from the baseline year. Similarly the state-of-charge swing for hybrid modeling of 30-70% is reasonable, but does not reflect improved battery technology for the 2020-25 period, which should allow a greater swing for reduced battery size, weight, and cost.	EPA and Ricardo appreciate the comment. Future analyses could consider modifications to assess more aggressive reductions in transmission losses and improvements in battery technology.	5.2, 8.1
Simulation methodology	Major deficiencies in the report	202	Descriptions of the algorithms used for engine control, transmission control, hybrid system control, and accessory control were not provided.	See revised section 6.	6
Simulation methodology	Vehicle model issues	209	Although the report described the major powertrain subsystems included in the vehicle models (page 24), a description of the vehicle model was not provided.	See revisions to section 6, including addition of Figure 6.1.	6
Recommendations	Specific recommendations for improvements	234	Provide an overall schematic and description of the powertrain and vehicle models. a. Show all of the subsystem models/maps used in the overall model. b. Show the format of the information in each of the subsystem models (including input, subsystem model, output).	See revised section 6.	6
Inputs and Parameters		302	The simulation methodology is generally not described in the report in sufficient detail to assess the validity and accuracy of the approach. The models and approach are described qualitatively; however, this is insufficient to truly evaluate the ability of the modeling approach to perform the desired function. The following subsections address specific issues with the models, inputs, and parameters and suggest possible corrective actions to address these issues.	See revised section 6.	6

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	Vehicle model issues	304	List the dynamic equation describing the longitudinal motion of the vehicle.	Dynamic equations for longitudinal motion are those incorporated within the MSC.Easy libraries.	6
Inputs and Parameters	Engine technology selection	342	There are a host of different technologies superimposed to create the future powertrain technologies. There is not a clear process described on how this technology "stack-up" is achieved. For instance, an advanced engine technology may allow for greatly improved BMEP. Greatly improved BMEP often comes at the expense of knock limits which are difficult to model even with sophisticated modeling techniques. In this simulation, many layers of powertrain technology are being compounded upon each other which will not simply sum up to the best benefits of all of the technologies – there are simply too many interactions. At the level of modeling described, which are maps which are altered in various unspecified ways; it is not clear how the technology stack-up is captured.	This is the purpose of the empirically derived model and BSFC maps - to avoid technology "stackup". These have been accounted for as Ricardo has based maps on real engines with much of this content already. Knock issue is redundant with other comments (see other responses).	6
Recommendations	Vehicle model issues	381	List the dynamic equation describing the longitudinal motion of the vehicle a. NOT ADDRESSED IN SUPPLEMNTAL MATERIAL REVIEWED	See Excerpt 1.	6
Recommendations	Vehicle model issues	382	List all parameters used for each vehicle class for simulation a. NOT ADDRESSED IN SUPPLEMNTAL MATERIAL REVIEWED	Please see expanded baseline attributes table in appendix	6
Simulation methodology		91	Was coast-down data from the baseline vehicles obtained or where the coefficients of rolling resistance and Cd modified to get the data to match?	See revised Sections 6.1 and 7.1.	6.1
Results	6.1 Baseline Conventional Vehicle Model	106	Results were compared to the EPA Vehicle Certification Database. These results often include correction factors and allowances that aren't documented on the sticker. Recommend that actual testing be run to perform the benchmark.	The report accurately describes what was done for this study. The Certification Database information comes from actual tests performed on the baseline vehicles using actual unadjusted results.	6.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations		154	Should use coast down data for baseline vehicles to model parasitic losses.	See revised Sections 6.1 and 7.1.	6.1
Simulation methodology	Major deficiencies in the report	199	An overall schematic and description of the powertrain and vehicle models and the associated subsystem models/maps were not provided. Only vague descriptions were included in the text of the report.	See revised report Section 6.1, including new Figure 6.1.	6.1
Simulation methodology	Vehicle model issues	210	Issue: A description of how aerodynamic losses, tire rolling losses and weight are handled in the model was not provided.	The starting point for the vehicle models was to use the existing road-load coefficients from the EPA Test Car List, which are represented as the target terms for the chassis dynamometer. Known as target A-B-C terms, the coefficients were used to derive the physical properties of rolling resistance, linear losses, and aerodynamic drag. These properties were then used in the simulation to provide the appropriate load on the vehicle at any given speed. See revised Sections 6.1 and 7.1.	6.1
Simulation methodology		297	The vehicle model is reported as “a complete, physics-based vehicle and powertrain system model” - which it is not. The modeling approach used relies heavily on maps and empirically determined data which is decidedly not physics-based. This nomenclature issue aside, the model is not described in sufficient detail in the report to make an assessment in this area. An excellent example of this is the electric traction drives and HEV energy storage system for which the report mentions no details, even qualitative ones, on the structure of the models.	See revised section 6.1.	6.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Vehicle model issues	303	The vehicle model is described as "a complete, physics-based vehicle and powertrain system model" developed in the MSC.Easy5TM simulation environment. This description is not particularly helpful in defining the type of model as portions of the model are clearly not physics based, such as the various empirical maps used or sub-models like the warm-up model which is by necessity an empirical model due to the complexity of the warm-up process compared to the expected level of fidelity of the model. It is assumed that a standard longitudinal model accounts for rolling losses, aero losses, and grade is used to model the forces acting on the vehicle. Input parameters for the vehicle model are not described. The baseline vehicle platforms are listed, however, the relevant loss coefficients are not provided (rolling resistance, drag coefficient, inertia.)	See revised Section 6.1. Baseline vehicle parameters are tabulated in Appendix 3.	6.1
Inputs and Parameters	Baseline vehicle subsystem models/maps	163	Recommendation: Since the baseline vehicles modeled were 2010 production vehicles, the models/maps for the subsystems used in these vehicle models should be included in the report before it is released.	It is important to note that, following the model validation phase, baseline vehicles were not established just using the given EPA Test List data or the raw validated vehicle fuel economy results. Rather than using the raw validation vehicles and corresponding fuel economy results, a new set of baseline values were determined to facilitate a uniform comparison between the advanced (future) concepts and today's current technologies.	6.1, 6.2

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations		240	Recommendation: Since the baseline vehicles modeled were 2010 production vehicles, the models/maps for the subsystems used in these vehicle models should be included in the report before it is released.	It is important to note that, following the model validation phase, baseline vehicles were not established just using the given EPA Test List data or the raw validated vehicle fuel economy results. Rather than using the raw validation vehicles and corresponding fuel economy results, a new set of baseline values were determined to facilitate a uniform comparison between the advanced (future) concepts and today's current technologies.	6.1, 7.1
Results		44	There is also no baseline hybrid configuration and no validation of the hybrid model. Due to the increased complexity of these vehicle systems, it is important to ensure the parameters and assumptions are valid.	No validation was performed for the hybrid architectures as no P2 hybrid vehicles were in production during the study. The Small Car with P2 architecture was simulated at comparable road loads to the Toyota Prius, and the fuel economy figures were higher than the current Prius. Section 6.2 presents the baseline hybrid configurations. The revised Section 6.8 more fully describes the hybrid approach used for this study.	6.2, 6.8, 7.1
Inputs and Parameters	Baseline vehicle subsystem models/maps	164	A major omission was that a baseline model of a hybrid vehicle, which is significantly more complex than the baseline vehicle, was not developed and compared to available EPA fuel economy test data for production hybrid vehicles.	No P2 hybrids in production now, so nothing to validate against. Any production vehicle would be optimized for specific engine/electric machine/battery. Study assumption assumed leave a generic, accurate controller that would cover the design space. Also, a Hybrid baseline was not part of the scope; therefore it can't be compared to the 2011 Hyundai Sonata Hybrid. See revised Section 7.1 for further discussion.	6.2, 7.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Baseline vehicle subsystem models/maps	165	Recommendation: A baseline model of a hybrid vehicle should be developed and compared to 2010 EPA fuel economy test data for production hybrid vehicles.	No P2 hybrids in production now, so nothing to validate against. Any production vehicle would be optimized for specific engine/electric machine/battery. Study assumption assumed leave a generic, accurate controller that would cover the design space. Also, a Hybrid baseline was not part of the scope; therefore it can't be compared to the 2011 Hyundai Sonata Hybrid. See revised Section 7.1 for further discussion.	6.2, 7.1
Inputs and Parameters	6.3 Accessories	73	I think the assumption that LDT cooling fans will be engine driven is incorrect. The new F150's have electric fans.	This issue was not considered significant enough to warrant considering re-running the model runs. If the commenter is correct in gauging the likely normal configuration in the future, the result would be some modest gain in fuel efficiency and reduced CO2 emissions.	6.3
Simulation methodology		93	Regarding engine downsizing, I'm not sure that the scaling approach applies to boosted engines, especially engine with multiple compressors as well as DVT and CPS technology.	Scaling method, including heat loss effects are a standard energy approach. All SI engines use SI scaling curve. Methodology is applicable to DI Turbo engines based on Ricardo experience. See revised Section 6.3.	6.3
Simulation methodology		94	Turbo lag applied as a first order transfer function with a time constant. How was the time constant selected? Was it validated? How was the improvement attributed to turbo compounding modeled?	Time constant selected based on professional experience, and validated against data shown in Figure 4.5. See revised Section 6.3 for further discussion on how the various improvements were modeled.	6.3
Inputs and Parameters	Engine technology selection	167	Setting the minimum per-cylinder volume at 0.225L and the minimum number of cylinders at 3 is appropriate. However, achieving customer acceptable NVH with 3 cylinder engines continues to be problematic.	3-cylinder engines have been in production for many years, and Ford has plans for a boosted 3 cyl in 2013.	6.3

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Engine Scaling	289	The report states, "The BSFC of the scaled engine map is …adjusted by a factor that accounts for the change in heat loss that comes with decreasing the cylinder volume, and thereby increasing the surface to volume ratio for the cylinder" (page 26). This is a directionally correct correction. However, specific values for the correction should be provided, together with references to the data and methodology used to derive the values used.	The correction factors are derived from Ricardo data from benchmarking and development programs.	6.3
Other Comments	Engine Scaling	290	Issue: The report states, "…downsizing the engine directly scales the delivered torque, …" (page 26). However, since there will be increased heat loss from the smaller displacement cylinder, the torque would be expected to be less than the directly scaled values for the same fueling rate.	The fueling rate itself is modified with scaled torque. It is never stated that the torque is the same for a given fueling rate.	6.3
Inputs and Parameters	Engine Models	307	The engine models are "defined by their torque curve, fueling map, and other input parameters." This implies that the maps are static representations of fuel consumption versus torque, engine speed, and other unknown input parameters. Generally speaking, representing engine performance in this fashion is consistent with typical practice for this class of modeling. This comment deals only with the representation of the engine performance in simulation, the generation of the data contained within the map is much more challenging.	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	6.3
Inputs and Parameters	Engine Downsizing	329	Engine scaling is used extensively in the report. Basic scaling based on brake mean effective pressure is common in modeling at this level of fidelity, thus, this does not need any special description. However, the report mentions some means of modeling the increased relative heat loss with small displacement engines which is not a standard technique. The model or process used to account for this effect should be explicitly described given that engine size is one of the key parameters in the design space.	See revisions to section 6.3 and new Figure 6.2.	6.3

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	Engine Downsizing	330	Properly document the process of scaling engines.	See revised section 6.3.	6.3
Recommendations	Engine Downsizing	331	Validate the process used to scale engines.	Engines were scaled linearly, with regard to displacement and torque. The brake specific fuel consumption maps were modified based on a heat loss effect curve. The curve represents data and simulation results that indicate a benefit in BSFC with increased individual cylinder size.	6.3
Simulation methodology	Scaling Methodology Review	393	With one exception, the scaling methodology appears to be sound given the information provided in the presentation. The curve used to adjust BSFC with displacement ratio is not supported with data or any citation of where it originated. The motivation for this correction seems valid, however, it needs to be supported with data.	EPA and Ricardo acknowledge and appreciate the reviewer's comments. See revisions in section 6.3.	6.3
Inputs and Parameters		402	Engine Model: I see data on the HEDGE engine technology but no mention of it in the list of engine technologies unless it's the high EGR DI gasoline engine.	The HEDGE is an example of the EGR DI engine.	6.3
Inputs and Parameters	Engine technology selection	168	Issue: The description of the derivation of all of the engine models/maps was insufficient.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them. Also, on specific maps relevant to the engine model, we note that the effects of the valve actuation system, fueling system, and boost system were integrated into the final torque curves and fueling maps, therefore subsystem performance maps, such as turbine and compressor efficiency maps, are not relevant to this study.	6.3, 6.8

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		25	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: Details of warm-up model parameters, such as ambient temperature; warm up friction correction; cold start fuel consumption correction factor; generation of heat rejection maps for various combinations in the simulation matrix.	After reviewing the overall comments, Ricardo and EPA did not believe that adding significant detail to the warm-up model discussions in the final report would assist in the overall presentation of the study findings.	6.3.1
Simulation methodology	Warm-up methodology (Section 6.3.1)	37	Specific suggestions regarding models that need more detailed coverage: This section talks about using engine warm-up profile during the cold start portion to ascertain additional fueling requirements. It talks about a correction factor to account for this additional fuel. How was this factor determined? Has a different correction factor been used for various engines? For instance, for a lean-burn engine that reject less heat, the oil warm-up is slower compared to a baseline engine. Was a new heat rejection map generated to account for start-up enrichment while modeling the warm-up? What is the ambient temperature that has been considered while performing the FTP 75 fuel economy test? Have the viscous effects of engine oil considered in the warm up simulation? How have the friction losses for various valvetrain engine combinations been modeled?	See revised section 6.3.1 for warmup assumptions.	6.3.1
Results	Section 4.5.1 Intelligent Cooling System	104	The system as described seems more appropriate for regulated emissions reduction opportunity rather than fuel economy or GHG. I think these systems enable engine control strategies that aren't part of this study that would have a greater impact on fuel economy than warming up the engine faster.	See revised section 6.3.1.	6.3.1
Other Comments	Warm-Up Methodology	285	"Ricardo used company proprietary data to develop an engine warm-up profile" which was used to increase the fueling requirements during the cold start portion of the FTP75 drive cycle (page 26). Since this data was proprietary, no assessment of its appropriateness can be made.	See revised section 6.3.1	6.3.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Warm-Up Methodology	287	Issue: No explanation was provided to clarify when the "engine warm-up profile" is used and when the "correction factor" is used. Therefore, the appropriateness of the warm-up methodology cannot be assessed.	See revised section 6.3.1.	6.3.1
Inputs and Parameters	Warm-Up Methodology	332	The report describes a 20% factor applied to bag 1 of the FTP-75 for baseline vehicles and a 10% factor applied to the advanced vehicles. The motivation for these factors is described qualitatively and is valid, as many organizations are currently investigating strategies to selectively heat powertrain components to combat friction effects. However, the values for these factors that were selected are not backed up with any data or citation. It is suspicious that the two values cited are such round numbers - the data from which these numbers are derived should be cited. Because of the complexity of this phenomenon, some type of empirical model is justified. The model described in the report is not sufficiently validated to judge its suitability.	See revised section 6.3.1.	6.3.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology	Cold Start Correction Methodology	384	The correction used to adjust fuel economy for cold start is described in this presentation. The method is based on two pieces of information: 1. A set of three tests from a single vehicle's instantaneous fuel multiplication correction factor 2. A piece of EPA data which shows a fleet-wide average for 2007 of the instantaneous fuel multiplication correction factor The instantaneous fuel multiplication correction factor is not described in the presentation, however, it is assumed to be the sum of the "short term fuel trim" and "long term fuel trim." If this is the case, then this value doesn't correlate to increased fuel consumption, but rather, to errors in the injector characterizations, fuel property assumptions, and air estimation algorithm in the engine controller. The engine controller is going to maintain stoichiometry based on oxygen sensor measurements, these trim values are the simply the feedback correction values required to do this based on the feedforward algorithm in the ECU. By way of example, I could alter the fuel tables of an ECU by 15% which would cause the feedback control system to correct by an opposite 15%. This would not change the fuel consumption of the vehicle once the control system has corrected it, which would happen in seconds. I don't disagree necessarily with the magnitude of the outcomes, since they are based mostly on EPA bag fuel economy data. If I am correct in my understanding of the correction factor then the method is not valid.	Section 6.3.1 details the warmup methodology for the study.	6.3.1
Inputs and Parameters		401	Battery Model: Overall the battery model is sound; however, I don't understand why cold modeling is included. The FTP testing doesn't include cold testing therefore only 25C and up should be included and the battery is consistent at those temps.	Cold testing was considered but not modeled in this study. See revised section 6.3.1.	6.3.1

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology	6.3.1 Warm-up Methodology	95	How was the engine warmup modeled? Is it a first order transfer function with a time constant? It said proprietary data was used, but how? Does the method allow for different warmup depending on size and engine technology?	Engine warmup assumptions are detailed in revised sections 6.3.1 and 6.7.	6.3.1, 6.7
Results	6.3.1 Engine Warmup Methodology	107	Were there hot and cold engine maps? No mention.	Engine warmup assumptions are detailed in revised sections 6.3.1 and 6.7.	6.3.1, 6.7
Results	6.7 Driver Model	115	How was the soak modeled? Were there hot engine maps and cold engine maps?	Engine warmup assumptions are detailed in revised sections 6.3.1 and 6.7.	6.3.1, 6.7
Simulation methodology	Accessories Models (Section 6.3.2)	38	Specific suggestions regarding models that need more detailed coverage: Alternator efficiency has been assumed to be constant around 55% for baseline. In the current baseline vehicles the alternator efficiencies do vary with the temperature and load.	The report accurately portrays how this issue was handled in the study. EPA and Ricardo will consider this issue for future analysis.	6.3.2
Simulation methodology	Accessories Models (Section 6.3.2)	39	Specific suggestions regarding models that need more detailed coverage: Has AC compressor load been considered in any of the simulations? In some of the new cycles being proposed by EPA, it is required that AC remains ON throughout the cycle. Hence, management of the AC load is very critical.	The study is based on 2-cycle FTP vehicle testing that does not include air conditioning to match current rulemakings.	6.3.2
Inputs and Parameters		74	Limiting the alternator to 200A is very conservative, particularly if the system voltage stays at 14V.	The use of a 200A alternator follows current production trends while streamlining the modeling process.	6.3.2
Simulation methodology	6.3.2 Accessories	96	Constant alternator efficiency and load is not a very good assumption. New alternator technologies and higher alternator loads due to electrification and increased electrical demands. Will the future still continue to use 14V or will higher voltages be used?	See small edits to this section to describe the assumptions used in the modeling, and the basis for those assumptions.	6.3.2

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Accessory load assumptions	186	Input values Alternator efficiency was increased from the current level of 55% to 70% to reflect "an improved efficiency design" (page 26 and 27).	The 55% to 70% alternator efficiency assumption is a legacy of the 2007-2008 EPA study. The value for the baseline and advanced design was discussed with Ricardo and was based on EPA's confidential discussions with suppliers.	6.3.2
Inputs and Parameters	Accessory load assumptions	187	Comment: Justification for the increase in alternator efficiency from 55% to 70% should be added to the report with references provided. Alternator efficiency as a function of speed and load may be more appropriate than a constant value.	Electrical accessory loads were assumed as constant value throughout drive cycle. Alternator efficiency map adds little value. Electrical loads over drive cycle are relatively small and with stop/start and "smart" management are relatively constant. Assumptions were considered reasonable by committee and are consistent with best practice in industry.	6.3.2
Inputs and Parameters	Accessory load assumptions	188	Accessory power requirements were not provided, such as shown in Figure 3-3 of PQA and Ricardo (2008), for example.	See accessory power requirements table.	6.3.2
Recommendations		245	Recommendation: Both mechanically driven and electrically driven accessory power requirements should be clearly provided in the report.	See Tables 6.3 and 6.4 in Section 6.3.2.	6.3.2
Other Comments	Accessory Models	269	None of the accessory models were not provided for review, so their adequacy and suitability cannot be assessed.	See accessory power requirements table.	6.3.2
Other Comments	Accessory Models	270	The accessory loads vs. engine speed for the conventional belt driven accessories were apparently removed from the engine when electric accessories were applied. However, the conventional accessory loads as well as the alternator loads/battery loads for the electric accessories were not provided.	See accessory power requirements table.	6.3.2
Other Comments	Accessory Models	271	In contrast, as an example, PQA and Ricardo (2008) provided the following map of an electric water pump and AC compressor drive efficiency. Similar maps for all accessory models would be expected in this report. (See Exhibit 6)	See accessory power requirements table.	6.3.2

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Accessory load assumptions	335	The accessory model is divided into electrical and mechanical loads. The electrical sub-model assumes alternator efficiency's of 55% and 70% for the baseline and advanced vehicles respectively. Given the required simplicity of the model, a simple model like this is likely acceptable, however, there is no source described for the alternator efficiencies. The base electrical load of the vehicle is mentioned briefly, however, no numerical values are given for each vehicle class or any type of model described.	The 55% to 70% alternator efficiency assumption is a legacy of the 2007-2008 EPA study. The value for the baseline and advanced design was discussed with Ricardo and was based on EPA's confidential discussions with suppliers.	6.3.2
Inputs and Parameters	Accessory load assumptions	336	The electrical system also includes an advanced alternator control which allows for increased alternator usage during decelerations for kinetic energy recovery. The control description given is valid but simplistic, but seems to fit the expected level of accuracy required for the purpose. There is an issue regarding with the approach for modeling the battery during this process. When charging the battery at the stated level of 200 amps, the charging efficiency of the battery will be relatively poor. During removal of the energy later, there will once again be an efficiency penalty. There is no description of a low-voltage battery model in the report nor any explicit reference to such charge/discharge efficiencies. Additionally, an arbitrary limit of a 200 amp alternator is defined for all vehicle classes – it is unlikely that a future small car and a future light heavy duty truck will have an alternator with the same rating.	The low voltage battery was based on a conventional 12 volt automotive battery. The efficiency of the battery itself was not specifically modeled. Several OE's have adopted the smart alternator energy recovery strategy. 200 Amp alternators already exist today. If there is the potential to recover all of the base electrical load during normal operation, then a 200 Amp alternator would be a small investment.	6.3.2
Inputs and Parameters	Accessory load assumptions	337	On the mechanical side, it is assumed that "required accessories" (e.g. engine water pump, engine oil pump) are included in the engine maps. The mechanical loading of a mechanical fan is mentioned but no description of the model which, at a minimum, should be adjusted based on engine speed and engine power.	The mechanical fan (only used on the trucks) was indeed modeled based on engine speed. See accessory power requirements table in report.	6.3.2

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	Accessory load assumptions	338	Cite and/or validate the alternator efficiency values of 55% and 70%.	The 55% to 70% alternator efficiency assumption is a legacy of the 2007-2008 EPA study. The value for the baseline and advanced design was discussed with Ricardo and was based on EPA's confidential discussions with suppliers.	6.3.2
Recommendations	Accessory load assumptions	339	Account for charge/discharge losses in the advanced alternator control and/or describe the 12V battery model used for the simulation.	See excerpt number 336.	6.3.2
Recommendations	Accessory load assumptions	340	Describe, cite, and validate the accessory fan model used in the simulation.	The load of the electrical cooling fan is included in the base electrical loads. Mechanical fans are included in the engine map.	6.3.2
Recommendations	Accessory load assumptions	341	Justify the use of a 200 Amp advanced alternator across all of the vehicle platforms.	The use of a 200A alternator follows current production trends while streamlining the modeling process.	6.3.2
Inputs and Parameters	Alternator Regen Shift Optimizer	385	The alternator regeneration strategy is not well documented. The key system specifications, such as max alternator output and efficiency, are listed as assumptions without a data source for validation. The efficiency of the battery is not mentioned in this nor other presentations that this reviewer has read – battery efficiency for a lead acid battery at high currents is poor, this would have an impact on the recovery of energy. Strategies like this are disruptive to drivability and this issue is not discussed in the presentation.	See excerpt number 336. In addition, drivability impact is minimal, as BMW already employs this technology on current production models.	6.3.2
Inputs and Parameters		404	Rgen Alternator: Ricardo states - 70% efficient alternator; however, alternator efficiency is a function of temp, speed and load. 70% is probably the best, but it's highly unlikely that it will operate there for the duration of the conditions.	As reader notes, 70% is today's best case scenario. It is a safe assumption that by 2020, 70% efficient alternators will be the norm. CBI from alternator manufacturers supports this.	6.3.2
Simulation methodology		413	Regen Alternator: Alternator model is too simplistic. On average the efficiency is too high as identified and it's unrealistic to assume that the battery will be able to accept 100% of the charge.	See response to Comment Excerpt 336.	6.3.2

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology	Transmission Models (Section 6.4)	40	Specific suggestions regarding models that need more detailed coverage: The transmission efficiencies vary by almost 10-15% based on the transmission oil temperature. How have these effects been modeled?	The warmup factor accounts for all engine, transmission and final drive gearing losses during bag1 and was derived from actual EPA test results.	6.4
Other Comments	Transmission Models (Section 6.4)	62	It is claimed that gear selection will be optimized for fuel economy for a given driver input and road load. Can this also be adaptive? Engine performance degrades with age. This strategy could also lead to more gear shifts; the latter would increase hydraulic loads and frictional power losses in the clutch, thus eroding some of the possible fuel economy gains.	See revised text in section 6.4 detailing comparison of optimized shifting to baseline production vehicles. Adaptive shift optimization to account for engine or powertrain degradation were not part of the scope of the study.	6.4
Simulation methodology	Section 6 Vehicle Models	89	No discussion of how driveline inertia is handled. This is important in forward-looking models.	Addressed in revisions to section 6.4.	6.4
Results	6.4 Transmission Models	108	Fig 6.1 appears to be a comparison of desired cvt ratio vs desired 6spd gear ratio. Should be stated as such. The shift logic controller should take into account the time to shift and whether or not the desired shift is achievable.	Plots desired CVT ratio vs. desired DCT gear ratios. Shift optimizer does account for time to shift and whether or not shift is desirable. The study also included a constraint on shift frequency. See revised section 6.4 detailing comparison of optimized shifting to baseline production vehicles.	6.4
Results		109	What are the shift optimizer inputs? What are it's basic decision criteria?	Shift optimizer inputs are discussed. Strategy tries to keep engine & trans at optimal efficiency. See revised section 6.4.	6.4
Results		110	There is no discussion of engine downspeeding.	Engine downspeed not a first-order strategy, in some cases it was the result of the optimized shift strategy.	6.4
Results		111	There is no discussion of gear ratio selection.	Gear ratios are now included in section 6.4.	6.4
Completeness		137	No transmission data was shown. No mass, no inertia to efficiency maps, no gear ratios.	The transmission models use inertia values comparable to contemporary production. See revised Section 6.4.	6.4

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness	Section 6 Vehicle Models	143	No discussion of how driveline inertia is handled. This is important in forward-looking models.	Addressed in revisions to section 6.4.	6.4
Inputs and Parameters	Transmission technology selection	174	The forecast that current 4-6 speed automatic transmissions will have 7-8 speeds by 2020-2025 is appropriate for all except the smallest and/or low cost vehicles (page 19).	EPA and Ricardo appreciate the comment; no further response is required.	6.4
Inputs and Parameters	Transmission technology selection	176	Recommendation: The detailed assumptions showing how the benefits of dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants were added to the transmission maps should be added to the report before it is released.	See revisions to section 4.4 and 6.4 in the final report.	6.4
Simulation methodology	Transmission optimization	207	A transmission shift optimization strategy is presented in the report and the results are shown in Figure 6.1 (page 28). This figure shows very frequent shifting, especially for 4th, 5th and 6th gears.	See revised text in section 6.4 detailing comparison of optimized shifting to baseline production vehicles.	6.4
Simulation methodology	Transmission optimization	208	Issue: Optimized shift strategies of the type used by Ricardo have been previously evaluated and found to provide customer complaints of "shift busyness". Customers are likely to reject such a shift strategy.	See revised text in section 6.4 detailing comparison of optimized shifting to baseline production vehicles.	6.4
Recommendations		242	Recommendation: The detailed assumptions showing how the benefits of dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants were added to the transmission maps should be added to the report before it is released.	See revisions to section 6.4 in the final report.	6.4

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Inputs and Parameters	Shift Optimizer	386	Shifting strategy impacts efficiency, performance, and drivability. Manufacturers are aware of this and balance all three when calibrating shift maps. Changing baseline shift maps to improve efficiency will have an impact on the other metrics which are also important to the vehicle. Additionally, it is not clear how the optimized shift strategy was developed, what the shift strategy is, or how it will be applied to the range of transmissions in the study. It is stated that is optimizes BSFC, however, there are other constraints that must be applied in addition to this.	Your points are valid. The shift optimizer model had many constraints at the expense of fuel economy. The result was a similar number of shifts over the cycle as compared to the baseline vehicle and improved fuel economy. See revised section 6.4 for more detail.	6.4
Inputs and Parameters	Input Data Review	398	The shift strategy is discussed qualitatively; however, it is not described in enough detail to understand exactly how it is accomplished. Shift schedules are shown, however, no validation is shown that would indicate that these shift schedules are optimal as claimed.	See revised section 6.4.	6.4
Simulation methodology		410	Transmission Model: Ricardo describes an approach that asserts that using an average efficiency value vs a 3D efficiency map yields insignificant differences over the CAFÉ drive cycles, but offers no results to validate the claim.	See revised section 6.4.	6.4
Simulation methodology		411	Transmission Model: Ricardo offers no discussion of how inertial changes are managed during shifts. This may have greatest impact on the shift strategies where the transmission shifts to put the engine at the best bsfc for the given load.	The transmission model only captures efficiency and torque/speed for each gear. Shift duration is fixed and is already explained in report (6.4). How "this may have greatest impact on the shift strategies" needs further explanation from reviewer. Completely ignoring all of the rotating inertias in these light duty vehicles would probably affect the result by only 3%.	6.4
Results	6.5 torque Converter models	112	The lockup strategy seems very conservative. Large gains are achievable with more sophisticated control and are in use today.	See revised text in section 6.5.	6.5

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Results		113	What was the basis for the minimum rpm's for lockup sited? Should be based on lugging the engine. The controller should recognize when it needs to unlock the TC based on the engines ability to keep up.	The transmission controller prevented the engine from extreme lugging. The torque converter never locks at operating points where the engine cannot keep up or drivability diminishes.	6.5
Inputs and Parameters	Input Data Review	399	The torque converter models are standard models, thus, the provided documentation is adequate.	EPA and Ricardo appreciate the comment; no further response is required.	6.5
Results	6.6 Final Drive Model	114	Only discussed the baseline, what improvements for 2020 and what final drive selection criteria for the future vehicles was used?	Final drive ratio was one of the swept parameters in the Design of Experiments matrix. This allows the user to select from a range of final drive ratios.	6.6
Results		5	Performance calculations tied to the FTP, HWFET, and US06 test cycles do not adequately capture vehicle behavior under real-world operation. Therefore, technologies that address improving fuel economy under real-world operation are either excluded or their contribution not included. The application of a 20% reduction in fuel economy to the FTP75 bag 1 portion of the drive cycle for 2010 baseline vehicles and 10% for 2020-2025 is crude, arbitrary, and treats only one of many problems with the driving simulation in the test cycles. Test cycle difficulties carry over into the simulation of hybrid control strategies.	The 20% value was based on actual results of EPA certification testing in the 2007 timeframe when it was applied. Current BMWs with electric water pumps exhibit an 11% to 12% warmup penalty on bag1 mpg (2011 EPA Test Car List Cert data) and EPA felt that an assumption of 1% to 2% further improvement was attainable. The EPA test cycles were not chosen arbitrarily as they are the basis for past as well as future fuel economy standards. Their relationship to "real world" fuel economy is well known and documented by EPA but does not serve to alter the legacy EPA Cert tests that will be used for 2020-2025 fuel economy regulations. See excerpt 333.	6.7

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments	Warm-Up Methodology	286	Elsewhere the report states, "A bag 1 correction factor is applied to the simulated "hot" fuel economy result of the vehicles to approximate warm-up conditions…" The correction factor reduces the fuel economy results of the FTP75 bag 1 portion of the drive cycle by 20% on the current baseline vehicles and 10% on 2020-2025 vehicles that take advantage of fast warm-up technologies" (page 29). No references or data are cited to support this significant reduction in correction factor.	See excerpt 333.	6.7
Recommendations	Warm-Up Methodology	333	Cite sources of data for 10% and 20% factors applied to the cold bag fuel economy data.	The 20% value was based on EPA test data and a legacy of the 2007-2008 study and was retained for current technology vehicles without electric water pumps or other advanced technologies that improve vehicle/powertrain warmup. Current BMWs with electric water pumps exhibit an 11% to 12% warmup penalty on bag1 mpg (2011 EPA Test Car List Cert data) and EPA felt that an assumption of 1% to 2% further improvement was attainable. This was based on the Ford Escape warmup data measured by Argonne Natl Lab, which was better than Ricardo's model data at the time. If today's Ford and BMW engines could achieve a 0.88 factor on bag 1, it seems reasonable to expect future engines to achieve that.	6.7
Inputs and Parameters		75	Is there any accounting for the energy conversion on hybrids from the high voltage bus to the low voltage?	The DC-DC converter has specified efficiency characteristics. See section 6.8.	6.8
Simulation methodology	6.8 Hybrids	97	Were separate optimization runs to determine the best control strategy done? How are we assured the best control strategy is implemented?	See revised Section 6.8, which includes significant additional text and figures to address these concerns.	6.8

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness	Section 4.3 Hybrids	133	Don't see any data on the battery technology, battery management, SOC control strategies. No discussion of regen braking strategies.	Ricardo and EPA decided on generic Li-ion battery technology that was equivalent to best today. See further discussion in section 6.8.	6.8
Completeness	6.8 Hybrid Models	145	Too much data is missing. What were the pack voltages? What were the battery technologies? Was there only one or more? Other than improved resistance, what other future improvements were included, like improved power density, improved usable SOC range? What was the control strategy for each type?	See revised Section 6.8, which includes significant additional text and figures to address these concerns.	6.8
Completeness		146	Load leveling the engine by charging the batteries has been shown to not be a very good idea because the round trip efficiency hit is a killer. Should only be used when SOC falls below a certain level.	Load averaging was the approach chosen by the full study team. If the engine is on, the study assumes that operate at most efficient point. Ricardo made a side comparison to evaluate this issue; definitely better W/P2. See the revised section 6.8.	6.8
Completeness		147	We're left to assume that SOC leveling is accomplished, but there is no description of how? Was an EPA/SAE method used.	See revised section 6.8	6.8
Inputs and Parameters	Hybrid technology selection	178	Issue: The adequacy of the P2 Parallel and PS Power Split Hybrid systems cannot be determined without having, at a minimum, schematics and operational characteristics of the each system together with comparisons with today's hybrid systems.	See revisions to Section 6.8.	6.8

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Hybrid technology selection	179	Although not contained in the report, the teleconference call EPA on May 5, 2011 revealed that 90% of the deceleration kinetic energy would be recovered. Kinetic energy recovery is limited by the following: - Maintaining high generator efficiency over the range of speeds and resistive torques encountered during deceleration - Limitations on the rate at which energy can be stored in the battery - Losses in the power electronics - Some energy is lost when energy is withdrawn from the battery for delivery to the motor. - Inefficiencies in the motor at the speeds and torques required. The inefficiencies of each of these four subsystems are in series and are compounded. If each subsystem had 90% efficiency, the kinetic energy recovery efficiency would be only 66%.	Your points are valid. To clarify: The model assumes that 90% of the mechanical braking energy will be performed by the hybrid electrical system (not recovered) and less than 90% would be stored and even less available for mechanical reuse due to system efficiencies. All of this has been accounted for in the hybrid model. See revisions to Section 6.8 to clarify these points.	6.8
Inputs and Parameters	Hybrid technology selection	180	Issue: Capturing 90% of the deceleration kinetic energy is a significantly goal. The technology to be used to achieve this goal needs to be explained and appropriate references added to the report.	Your point is valid. To clarify: The model assumes that 90% of the mechanical braking energy will be performed by the hybrid electrical system (not recovered) and less than 90% would be stored and even less available for mechanical reuse due to system efficiencies. All of this has been accounted for in the hybrid model. See revisions to Section 6.8 to clarify these points.	6.8
Inputs and Parameters	Battery SOC swing and SOC	190	Although not contained in the report, an email from Jeff Cherry (EPA) on May 5, 2011 revealed that the SOC swing was 30% SOC to 70% SOC or 40% total, which appears to be appropriate.	Section 6.8 of the report has been revised to include the 40% SOC value.	6.8

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Results	Sample runs of CSM	215	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Stoichiometric DI Turbo with Stop-Start to PS Hybrid - 11.1% improvement in M-H mpg - A detailed explanation of the differences in the improvements between the P2 and PS hybrids should be provided in the report, especially considering that the P2 hybrid has better fuel economy and uses a 70% smaller electric motor (24 vs. 80 kW).	The P2 hybrid architecture has better driveline efficiency than the Powersplit type. Also, despite having a smaller electric machine than the Powersplit traction motor, both EM's are able to regenerate at least 90% of the braking energy on the drive cycles.	6.8
Results	Sample runs of CSM	216	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Stoichiometric DI Turbo PS Hybrid to Naturally Aspirated Atkinson CPS Hybrid - Loss of 2.3% M-H mpg (From Stoichiometric DI Turbo PS Hybrid) - The details of the Naturally Aspirated Atkinson CPS Hybrid should be provided to explain the nearly equal fuel economy to the Stoichiometric DI Turbo PS Hybrid.	One of the advantages of hybridization is the ability to operate the engine near its most efficient point. In this case, the Atkinson engine had a better best BSFC region compared to the Stoichiometric DI Turbo engine.	6.8
Results	Sample runs of CSM	217	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Stoichiometric DI Turbo PS Hybrid to Naturally Aspirated Atkinson DVA Hybrid - 2.1% M-H mpg improvement in M-H mpg (From Stoichiometric DI Turbo PS Hybrid) - The details of the Naturally Aspirated Atkinson DVA Hybrid should be provided to explain the nearly equal fuel economy to the Stoichiometric DI Turbo PS Hybrid	See response to Comment Excerpt 216.	6.8

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Other Comments	Hybrid Technologies Models	265	Key elements of a hybrid system include: electric machines (motor-generator), power electronics, and a high-voltage battery. Only the following vague description of the models for these subsystems was provided: "For each of these systems, current state of the art technologies were adapted to an advanced 2020-2025 version of the systems, such as by lowering internal resistance in the battery pack to represent 2010 chemistries under development and decreasing losses in the electric machine and power electronics to represent continued improvements in technology and implementation" (page 29). This vague description did not provide adequate details to assess the adequacy of these models. For example, specific values for internal resistance with references should be provided together with an illustration of how this was incorporated in the model of the battery.	See revisions to section 6.8.	6.8
Other Comments	Hybrid Technologies Models	268	No mention was provided of how the cooling system for the hybrid system was modeled.	The hybrid power electronics and motors were assumed to be water cooled with the waste heat added to the cooling load of the vehicle based on the efficiencies described in the report.	6.8

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Inputs and Parameters	Hybrid technology selection	345	Hybrid vehicles are particularly challenging to model because of the extra components which allow multiple torque sources, and thus, require some form of torque management strategy (i.e. a supervisory control.) The report briefly describes a proprietary supervisory control strategy that is used to optimize the control strategy for the FTP, HWFET, and US06 drive cycle. The strategy claims to provide the "lowest possible fuel consumption" which seems to be somewhat of an exaggeration – this implies optimality which is quite a burden to achieve and verify for such a complicated problem. The strategy also is reported to be "SOC neutral over a drive cycle" which is also difficult to achieve in practice in a forward looking model. Once can get SOC with a certain window, however, short of knowing the future or simply not using the battery - it is impossible to develop a totally SOC neutral control strategy.	The powertrain operates at near best fit, and thus is expected to provide very good fuel consumption. But, it is not optimized over the whole design space. Ricardo has adjusted the "lowest possible..." language and added a state flow diagram. See revised section 6.8.	6.8
Inputs and Parameters	Hybrid technology selection	347	Without even basic details on the hybrid control strategy, it is simply not possible to evaluate this aspect of the work. Because of the batch simulations with varying component sizes and characteristics, this problem is not trivial. Supervisory control strategies used in practice and in the literature require intimate knowledge of the efficiency characteristics and performance characteristics of all of the components (engine, electric motors/inverters, hydraulic braking system, and energy storage system) to develop control algorithms. This concern is amplified by the lack of validation of the hybrid vehicle model against a known production vehicle. It is unclear how a "one-size fits all" control strategy can be truly be perform near optimal over such widely varying vehicle platforms.	See revised section 6.8.	6.8

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	Hybrid technology selection	350	Validate that the HEV control algorithm performs equally well on all vehicle classes.	The class of vehicles does not change the hybrid control strategy. The different roadload effects of the various classes change the level of benefit from hybridization: however, the goal of maximizing efficiency through recovering brake energy and operating the engine at low BSFC points remain the same.	6.8
Inputs and Parameters	Electric Traction Components	352	The model of electric traction components is not discussed in any detail, as the only mention in the report is that current technology systems were altered by "decreasing losses in the electric machine and power electronics." Given the importance of the electric motor and inverter system in hybrids this is not acceptable.	See significant revisions to section 6.8.	6.8
Recommendations	Electric Traction Components	353	Describe the method used to model electric traction components.	See expanded discussion of hybrid models in section 6.8.	6.8
Recommendations	Electric Traction Components	354	Provide validation/basis for the process used to generate future technology versions of these components.	Part of Row 329; see expanded discussion of hybrid models in section 6.8.	6.8
Recommendations	Electric Traction Components	355	Describe the technique used to scale these components.	Part of Row 329; see expanded discussion of hybrid models in section 6.8.	6.8
Inputs and Parameters	HEV Battery Model	356	Battery models for HEVs are necessary to adequately model the performance of an HEV. The report provides no substantive description of the battery pack model, other than that the model was developed by "lowering internal resistance in the battery pack to represent 2010 chemistries under development." Battery pack size is also not a currently a factor in the model – this has a impact of charge and discharge efficiency of the battery pack.	See significant revisions to section 6.8.	6.8
Recommendations	HEV Battery Model	357	Describe the method used to model the HEV battery.	See revisions to section 6.8.	6.8
Recommendations	HEV Battery Model	358	Provide validation/basis for the process used to generate future technology versions of the battery.	See revisions to section 6.8.	6.8

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	HEV Battery Model	359	Describe the technique used to scale the HEV battery .	See revisions to section 6.8.	6.8
Inputs and Parameters	Battery Warm up 1, Battery Warm up 2	387	The battery model described has the following possible problems: The model is relatively simple – but could potentially work for the application and generally is consistent with the fidelity of the rest of the model.	EPA and Ricardo appreciate the comment; no further response is required.	6.8
Inputs and Parameters	Battery Warm up 1, Battery Warm up 3	388	The battery model described has the following possible problems: The model references ambient temperature for heat rejection. Most HEVs pull in cabin air rather than outside air for cooling, thus, this will cause modeling error.	The drive cycles covered in this study represent cabin temperatures similar to the ambient test temperatures.	6.8
Inputs and Parameters	Battery Warm up 1, Battery Warm up 4	389	The battery model described has the following possible problems: Adjusting the Mbat x Cpbat term by 200% is a red flag that something might be fundamentally wrong with either the model formulation or the data used in the model. There should be minimal errors in the mass estimation of the pack and the specific heats of battery modules can be found in the literature or through testing.	These parameters were not part of the Ricardo study.	6.8
Inputs and Parameters	Battery Warm up 1, Battery Warm up 5	390	The battery model described has the following possible problems: The method of handling battery packs of different classes of vehicles is not described, nor are the actual parameters for these different models disclosed.	See revised section 6.8 for details of sizing battery packs for the study.	6.8
Simulation methodology		412	Hybrid: I don't see any effort to model motor/inverter temperature effects. One would expect significant degradation of motor capability as things heat up during normal operation.	Motor/Inverter efficiencies were modeled as outlined in section 6.8 of the report at normal operating temperatures.	6.8

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Results		416	Motor Efficiency Maps: I am having trouble believing that motor efficiency will stay above 90% once temperature effects are accounted for. It also seems to me that these numbers don't include the inverter even though the authors say that it does. The UQM maps seem more reasonable. As stated in a previous comment, I believe that the cost reductions needed for motors will drop their efficiencies in the future.	Motor/Inverter efficiencies were modeled as outlined in section 6.8 of the report at normal operating temperatures. The efficiency map shown includes the inverter efficiency.	6.8
Inputs and Parameters		421	Carlson, R., et al., Argonne National Laboratory, On-Road Evaluation of Advanced Hybrid Electric Vehicles over a Wide Range of Ambient Temperatures EVS23 – Paper #275, 15 p. Paper reports on-road and dynamometer testing of two hybrid vehicles at cold (-14 degC) and hot (33 decC) conditions. Fuel economy increases with temperature (except for highest temperatures with the system which does not limit battery temperature). Comment: Paper provides data showing importance of temperature on hybrid vehicle fuel economy. These data are used by Ricardo to validate their battery warm up model, see next document.	EPA and Ricardo appreciate the comment; no response needed. Background materials included both highly relevant data and sources as well as some general information sources used during the course of the study. Not all sources reviewed were of critical importance to the study.	6.8
Simulation methodology		422	Ricardo, Hybrid Battery Warm Up Model Validation – Update, Light Duty Vehicle Complex Systems Simulation ,EPA Contract No. EP-W-07-064, work assignment 2-2, 15 Mar 10, 5 p. proprietary) This report presents a simple battery heat transfer model for battery warm up and compares with Argonne National Laboratory of the previous document. Comment: Model produces adequate prediction of battery temperature.	EPA and Ricardo appreciate the comment; no response needed.	6.8

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		425	Ricardo, Engine and Battery Warm-Up Methodology, Light Duty Vehicle Complex Systems Simularion, 17 Feb 10, 16 p. (proprietary) Document reviews engine and battery warm-up strategies and provides a simple model. Comment: The approach to battery warm-up is uncertain. Points to importance of test cycle (FTP for fuel economy compliance versus test for EPA label versus real-world).	Cold FTP was not included in this study.	6.8
Other Comments		429	Ricardo, Hybrid Controls Follow-up, 10 Sep 11, 3 p. (proprietary) Report discussed motor/general efficiency map used for 2020 technology. Projected efficiencies peak at 95% but most P2 hybrid application if below 90% efficiency. Comment: I am not qualified to assess if the projected motor/generator efficiencies are appropriate for 2020-2025 as reported, but they seem low for 15 years in the future.	The motor maps used in the study included the efficiency of the motor controller.	6.8
Other Comments	Hybrid Technologies Models	266	In contrast, as an example, Staunton et al. (2006) provided a detailed motor efficiency map, shown below, as well as efficiency maps of other key components of the Prius hybrid vehicle. Similar maps for all hybrid subsystems would be expected in this report. (See Exhibit 5)	See revisions to section 6.8.	6.8
Other Comments	Hybrid Technologies Models	267	In addition, "a Ricardo proprietary methodology was used to identify the best possible fuel consumption for a given hybrid powertrain configuration over the drive cycles of interest." (page 29), which precluded an assessment of its suitability.	See revisions to section 6.8.	6.8
Recommendations	Hybrid technology selection	349	Better describe the hybrid control strategy and validate against a current production baseline vehicle.	See revisions to section 6.8.	6.8

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	Hybrid Controls Presentations	400	Several hybrid controls presentations were provided, however, it was difficult to piece together what information superseded the other since they were provided out of context. There were several good slides showing dynamic programming results of different control scenarios, however, it is assumed that this was not used for the mass simulation since it would be computationally impractical. Thus, I expected to see some results comparing the offline control results to the actual control used in the vehicle simulation, however, this was not found. The major concern in this area is developing a control strategy that is near optimal for a wide variety of hybrid architectures as well as architectures with varying component types and sizes. Without further validation in this area it is not clear that the hybrid results are valid since the control has such an important role in this.	See revisions to section 6.8.	6.8
Recommendations	Warm-Up Methodology	334	Cite and/or validate the modeling approach used.	Please refer to the revised report concerning technology/model validation.	7
Results		42	For the vehicle performance simulation results shown in Table 7.1, were there any significant adjustable parameters used to fit these vehicles?	All vehicle parameters (road loads, mass, etc.) were the same for both cases in order to validate the models.	7.1
Results		43	Even though it appears that the validation results from the simulation have "acceptably" close agreement with the test data, there are up to 15% off. Even for the small car where all data is available, the error is on the order of 5%. These discrepancies are usually not negligible and should be taken into account when conclusions are drawn from the results, especially if regulation is to be proposed based on these.	EPA will take this into account in how it uses the final results to support rulemaking actions.	7.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments		55	It would be desirable to show the analysis used to convert fuel consumption savings to vehicle greenhouse gas (GHG) emissions equivalent output. Ultimately, what matters is the GHG savings resulting from the combined production and use cycle of alternative fuel options for combustion engines.	Appendix 3 to the final report presents the baseline fuel economy and CO_2 output equivalents for all classes of vehicles considered in this study. Note that the CO_2 equivalents used in these tables were provided by the EPA as 9,087 g/gal of fuel for gasoline and 10,097 g/gal for diesel.	7.1
Results	7.1 Baseline Conventional Vehicle Models	116	Better definition of what “acceptably close” means. This doesn’t meet the criteria for objectivity. Something like, “the advisory committee determined that the baseline models had to predict within x% to be usable for this study.”	The final report retains this text as is, because the text represents the approach taken during the study, during which EPA determined the results to be acceptable for moving forward. See revisions to section 7.1 to further describe the full process used to develop baseline vehicles.	7.1
Inputs and Parameters	Baseline vehicle subsystem models/maps	160	The development of baseline vehicle models with comparison of the model results to available 2010 EPA fuel economy test data was appropriate.	EPA and Ricardo appreciate the comment; no further response is required.	7.1
Simulation methodology	Baseline vehicle model validation results	204	Ricardo developed baseline vehicle simulations for 2010 vehicles for which EPA fuel economy data were available (page 30). “For the 2010 baseline vehicles, the engine fueling maps and related parameters were developed for each specific baseline exemplar vehicle.” (page 25). Even though these are production vehicles, the models and maps used were not described (including whether they were derived from actual measurements or models) and they were not provided in the report so that their appropriateness could not be assessed.	It is important to note that, following the model validation phase, baseline vehicles were not established just using the given EPA Test List data or the raw validated vehicle fuel economy results. Rather than using the raw validation vehicles and corresponding fuel economy results, a new set of baseline values were determined to facilitate a uniform comparison between the advanced (future) concepts and today’s current technologies.	7.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology	Baseline vehicle model validation results	205	Table 7.1 shows the calculated vs. EPA test data for the baseline vehicle fuel economy performance. This table should include percentage variation of the model calculations vs. the test data. The agreement of the model with the test data is within 11%, but this is a larger error than some of the incremental changes shown in Appendix 3. A closer agreement would have been expected.	Table 7.1 now compares validation model results with EPA Test List data for FTP and HWFET. All of the validation results are within 5%, with the exception of the Large MPV HWFET result, which is within 9.5% of the published value. The purpose of the validation model results is to provide a benchmarked starting point for the rest of the analysis.	7.1
Simulation methodology	Baseline vehicle model validation results	206	Recommendation: A closer examination of the reasons for the up to 11% discrepancies between the models and baseline vehicles' EPA fuel economy test data should be undertaken so that the models could be refined to provide better agreement.	EPA and Ricardo, together with the advisory committee, determined that the degree of agreement on fuel economy was adequate for this study. It is important to note that, following the model validation phase, baseline vehicles were not established just using the given EPA Test List data or the raw validated vehicle fuel economy results. Rather than using the raw validation vehicles and corresponding fuel economy results, a new set of baseline values were determined to facilitate a uniform comparison between the advanced (future) concepts and today's current technologies.	7.1
Recommendations		241	Recommendation: A baseline model of a hybrid vehicle should be developed and compared to 2010 EPA fuel economy test data for production hybrid vehicles.	During development of the PowerSplit model a modified small car with PS was simulated to validate the model but was not formalized for the report.	7.1

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations		247	Recommendation: A closer examination of the reasons for the up to 11% discrepancies between the models and baseline vehicles' fuel economy test data should be undertaken so that the models could be refined to provide better agreement.	Table 7.1 now compares validation model results with EPA Test List data for FTP and HWFET. All of the validation results are within 5%, with the exception of the Large MPV HWFET result, which is within 9.5% of the published value. The purpose of the validation model results is to provide a benchmarked starting point for the rest of the analysis.	7.1
Inputs and Parameters	Hybrid technology selection	346	Another factor that must be considered is that a hybrid strategy that achieves maximum fuel efficiency on FTP, HWFET, and US06 does not consider many other relevant factors. Performance metrics like 0-60 time and drivability metrics often suffer in practice. In today's hybrids, the number of stop-start events is sometimes limited from the optimum number for efficiency because of the emissions concerns. Because of these factors and others, a strategy achieving optimal efficiency may be higher than what can be achieved in practice.	The study approach used 0-60 time, max grade at different speeds, and other drivability metrics to make sure that the modeled vehicles had acceptable performance on core drivability issues. See the nominal test results in Section 7.1 and Appendix 5.	7.1
Inputs and Parameters	Hybrid technology selection	348	A last comment is that there is no validation of the HEV model against current production vehicles. At a minimum, the Toyota Prius has been dissected sufficiently in the public domain to conduct a validation of this class of hybrid electric vehicle.	No validation was performed for the hybrid architectures as no P2 hybrid vehicles were in production during the study. The Small Car with P2 architecture was simulated at comparable road loads to the Toyota Prius, and the fuel economy figures were higher than the current Prius.	7.1
Simulation methodology	7.2 Nominal Runs	98	Was a separate matrix of simulations run to obtain the nominal sizes for the advanced engine or was it merely a matter of matching the peak torque.	See revised section 7.2 for discussion.	7.2
Simulation methodology		99	How was a 20% reduction in engine size for the nominal hybrid engine arrived at? Even for the micro-hybrid (engine start/stop)?	The final report clarifies why 20% downsize of P2 & PS hybrids and all engines. Atkinson sized directly for hybrids. See Section 7.2. Adding to description of hybrid engine sizing methodology.	7.2

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology		100	"These summary results….used to assess the quality of the simulation…." Where is the data for this assessment published? What were the criteria that said pass or fail?	Appendix 5 presents the nominal test run results data.	7.2
Inputs and Parameters	Battery SOC swing and SOC	191	Achieving neutral SOC (neither net accumulation or depletion) for hybrid vehicle simulations is appropriate (page 30).	EPA and Ricardo appreciate the comment; no further response is required.	7.2
Results	8.2 RSM	119	A description of how the neural network is deployed is needed, only the why it was used is discussed in this section. What were the best fit criteria? What types of equations did the neural net have to play with? Where are the fit's published? How was it determined that the "one fit per transmission" was the best way to go?	The fit criteria were based on how well the regression line approximated the real data points from the DoE, using both the training data as well as the validation data.	8
Simulation methodology		369	The vehicle simulator is used to generate several thousand simulations using a DOE technique. This data is then fit with a neural-network-based response surface model in which the "goal was to achieve low residuals while not over-fitting the data." This response surface model then becomes the method from which vehicle design performance is estimated in the data analysis tool. In this case, the response surface model is nothing more than a multi-dimensional black-box curve fit. There was no error analysis given in the report regarding this crucial step. By way of example, the vehicle simulator could provide near perfect predictions of future vehicle performance; however, a bad response surface fit could corrupt all of the results.	See revised section 8.	8

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Results	8.1 Evaluation of Design Space	118	Why was Latin hypercube sampling methodology picked over other sampling methods? While it's attributes are mentioned, what other methods were considered?	As Section 8.1 states: "The method randomly samples the multidimensional parameter space in a way that provides comprehensive and relatively sparse coverage for best efficiency. It also allows one to efficiently continue to fill the multidimensional parameter space by further random sampling. It provides more flexibility than traditional multi-level factorial designs for assessing a large parametric space with an efficient number of experiments." Other, traditional, multi-level factorial designs were not feasible within the number of simulations to be performed within the scope of this study.	8.1
Recommendations		12	The design space should be expanded to include performance parameters, such as power/weight or 0-60 times.	Performance parameters are available in the RSM tool.	9
Results		46	The plots showing simulation results in blue, red, etc. could be better labeled (i.e. legends could be inserted in the plots) and possibly presented in a relative format indicating percent improvements over the baseline engine rather than absolute numbers. This is more of a personal choice for a more clear representation of the predicted improvement, rather than stating that there is anything wrong with the current representation.	EPA and Ricardo appreciate the comment; no further response is required.	9
Inputs and Parameters	Other inputs	194	The Design Space Query within the Data Visualization Tool allows the user to set a continuous range of variables within the design space range. Although this capability is useful for parametric studies, the following risks are incurred with some of the variables.	Ricardo is preparing a user guide for the tool to help address these types of concerns.	9
Inputs and Parameters	Other inputs	195	The sliders for "Eng. Eff" and "Driveline Eff." would allow the user to arbitrarily change engine efficiency or driveline efficiency uniformly over the map without having a technical basis for such changes.	The justification for the range of use for the input variables in a given situation is not part of this study	9

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Other inputs	196	The slider for weight would allow the user to add hybrid or diesel engines with signficant weight increases without incurring any vehicle weight increase.	The weight of technologies is not part of this study due to the complex nature and many opinions regarding this topic.	9
Inputs and Parameters	Other inputs	197	Recommendation: A default weight increase/decrease should be added for each technology. If weight reductions are to be studied, then the user should have to input a specific design change, with the appropriate weight reduction built into the model, rather that having an arbitrary slider for weight.	The weight of technologies is not part of this study due to the complex nature and many opinions regarding this topic.	9
Results	9.1 Basic Results	120	Why 10Hz sampling rate? By what criteria was a run considered good vs bad?	See footnote added to Section 9.1. Bad runs are those that failed to follow the cycle trace as described in EPA test procedures.	9.1
Results	9.3 Exploration of the Design Space	121	If boundaries of acceptable performance were applied, a considerable number of simulation runs could be eliminated.	The additional runs were needed to adequately fill the design space to allow the RSM tool user to obtain accurate results when changing input variables.	9.3
Other Comments		13	The conclusions, Section 11, are a reasonable summary of the work conducted.	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	11
Completeness		50	The “Conclusions” section of the report should be renamed “Summary” since it does not present any actual conclusions based on the results, but it does provide a summary of the project.	EPA and Ricardo appreciate the comment. The section name has been changed.	11
Recommendations		10	There should be a table describing the baseline vehicles.	See Appendix 3 in final report.	Appendix 3

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness		299	Based on the above, it is clear that this reviewer feels the report is inadequate at describing the entire process of modeling work from input selection to results. There was not a single subsystem that was documented at the level desired. It is understood that, in some cases, there are things of a proprietary nature that must be concealed. As a trivial example, the frontal area of the vehicle classes does not seem to be anywhere in the report or data analysis tool. This is one parameter amongst hundreds excluding the real details of the models (i.e. equations or block diagrams), methods used to generate engine maps, details on control laws, etc. On the topic of proprietary data, there are many ways of obscuring data sufficiently that can demonstrate a key point (i.e. simulation accuracy) without compromising confidentiality of data – this should not be a major barrier to providing some insight into the inner working of the simulator.	Baseline vehicle parameters are tabulated in Appendix 3.	Appendix 3
Recommendations	Vehicle model issues	305	List all parameters used for each vehicle class for simulation.	Baseline vehicle parameters are tabulated in Appendix 3.	Appendix 3
Completeness		125	It said there was a comprehensive list of technologies that the group started with, that list should be shown and a comment on why it wasn't included.	Complete technology selection list is now an appendix to the report.	Attachment A
Recommendations		151	Considerably more time in this effort is required up front in the report, to discuss the process of building consensus on data and models. Because this is not really discussed, it gives the impression that not much was done.	Please refer to the technology selection slides provided in the appendices to give the commenter a sense of the rigor of the technology selection process.	Attachment A
Recommendations		153	An uncertainty rating for each model/data set should be published to highlight the relative differences in the assumptions/extrapolation of future technologies.	Some level of uncertainty is provided in the technology selection slides provided in the attachment to the final report.	Attachment A

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Engine technology selection	166	The engine technologies selected for this study, listed in Table 5.1 (page 22), are appropriate, but are not all-inclusive of possible future engine technologies.	EPA and Ricardo appreciate the comment; no further response is required. The program team selected the set of possible technologies that appeared to provide the best suite of improvements and viability in the study time frame. See Attachment A to the final report for the full range of technologies initially evaluated.	Attachment A
Inputs and Parameters	Engine technology selection	170	Issue: There are many engine technologies that have potential for reduced GHG emissions that were not included in this study, such as: - Single stage turbocharged engines - Diesel hybrids - Biofueled spark ignition and diesel engines - Natural gas fueled engines - Other alternative fuel engines - Charge depleting PHEV and EV	EPA and Ricardo appreciate the comment. The program team selected the set of possible technologies that appeared to provide the best suite of improvements and viability in the study time frame. See Attachment A to the final report for the full range of technologies initially evaluated.	Attachment A
Completeness		230	There are many engine technologies that have potential for reduced GHG emissions that were not included in this study, such as: - Single stage turbocharged engines - Diesel hybrids - Biofueled spark ignition and diesel engines - Natural gas fueled engines - Other alternative fuel engines - Charge depleting PHEV and EV	EPA and Ricardo appreciate the comment. The program team selected the set of possible technologies that appeared to provide the best suite of improvements and viability in the study time frame. See Attachment A to the final report for the full range of technologies initially evaluated. Part of the evaluation process included expectation of market share based on cost, performance, and readily available fuel sources.	Attachment A
Inputs and Parameters	Future Friction Assessment	392	The provided presentation does not describe how engine friction projections to 2020 are made or how they are modeled. It provides some data from 1995 to 2005, however, it does not provide any useful insight into how this information is used.	Friction reduction improvements were extended from those used in the 2008 EPA study as described in Attachment A.	Attachment A

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness		450	Ricardo, Report on light-duty vehicle technology package optimization, 4 Dec 09, 32 p. This is a progress report on Ricardo's modeling work for the EPA. A range of engine technologies, hybrid technologies, transmission, and vehicle technologies are described. Comment: A comprehensive list of near term technologies are included. The report is incomplete and optimization apparent is not included here.	See Attachment A to final report.	Attachment A
Recommendations	Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness	244	Recommendation: To establish the adequacy of the subsystem models/maps, derivation details should be provided.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them.	General
Simulation methodology		3	Ricardo simulated dynamic vehicle physical behavior using MSC Easy5TM software with 10 Hz time resolution. This software and the time resolution are appropriate for the computations to show the effect of component interactions on vehicle performance. 10 Hz time resolution is sufficient to capture both driver behavior and vehicle response. Should the application of information technology, as is being implemented, as a means of vehicle control for reducing fuel consumption become a future strategy, the model should be able to provide a suitable simulation.	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology		4	Drivetrain synergistic effects seem to be predicted reasonably. This was demonstrated by calculation of fuel economy of the baseline vehicles and comparison with EPA certification test data. The model does not seem to have the capability to capture vehicle weight-drivetrain synergistic effects. Vehicle weight reductions associated with drivetrain efficiency improvements are input rather than modeled internally. This is an important deficiency. Similarly, from the Complex System Tool, weight reductions do not seem to result in reduction in engine displacement.	The mass of technologies was not included in this study due to the evolving nature and complex opinions regarding this topic. The user of the RSM tool is responsible to add or remove mass from the baseline vehicle to obtain the desired results.	General
Results		6	It is conceivable that BEVs and PHEVs (and less likely FCEVS) will be a significant part of the 2020-2025 vehicle fleet. That they are excluded from the model is a deficiency.	GHG reductions for PHEVs are calculated by applying a utility factor (percentage of BEV) to the results of this study for the appropriate hybrid vehicle.	General
Completeness		7	The selection of drivetrain technologies (other than the electric storage technologies) is comprehensive. The qualitative description of the drivetrain technologies is complete and clear, but quantitative performance data are missing. Transparency in the actual performance data is entirely lacking. This includes engine performance maps, shift strategies, battery management in hybrids, and more. That much of that data is proprietary to the companies that generated it and/or to Ricardo is a problem for what is proposed as a regulatory tool.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them.	General
Completeness		8	The assumptions are difficult to extract from the text.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations		9	The failure to model the drivetrain-weight interactions is a major shortcoming. Appendix 2 should clearly state that vehicle weights are held constant (assuming that I am correct in that assumption).	The mass of technologies was not included in this study due to the evolving nature and complex opinions regarding this topic. The user of the RSM tool is responsible to add or remove mass from the baseline vehicle to obtain the desired results.	General
Recommendations		11	Summarizing assumptions in tabular form would be a great assistance to the reader.	The final report includes a number of expanded tables and graphics to address this concern.	General
Other Comments		15	The report is intended to provide administrators, product planners and legislators a practical tool for assessing what is achievable, as well as insight into the complexity of the path forward to reach those advances that will be useful for productive discussions between EPA and the manufacturers. This path forward involves trade-offs among many design choices involving available, and soon-to-be-available advances in engine technologies, hybridization, transmissions and accessories. The current version of the simulation effort seems reasonably balanced in the attention paid to each of these areas. The range of improvements shown in the technologies considered and examples is encouraging.	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments		16	Overall, the project attempts to undertake an analytical technology assessment study of significant scope. It does a fairly competent job at analyzing a select number of technologies and packages, mostly aimed at improving the gasoline IC engine, and to a less extent the diesel engine. It complements improvements on the engine side with synergistic developments on the transmissions, hybrids and accessories. The main shortcoming of the study is that the methodology relies extensively on proprietary and undisclosed data, as well as empirical rules, correlations and modifiers without citing published reference sources. Beyond the perceived lack of transparency, keeping up with new technologies or approaches will necessarily involve new versions of the program since the actual models of the technologies used are proprietary and the choice and range of parameters available to users is fixed and to some extent hidden. Due to these constraints, the simulation tool is limited in its ability to provide fundamental insight; this will require a more basic thermodynamic approach, perhaps best carried out by universities.	The technology selections and combinations were selected to provide a representative group of combinations that reflect the thinking of the program team of some of the most common expected combinations across the range of light duty classifications. The full slate of options considered is set forth in Attachment A to the final report. In addition, while the use of proprietary data was a fundamental element of the study design, Ricardo has added significant details and graphics, including a number of publically available reference materials, to increase the transparency and overall utility of the final report. While EPA agrees that additional combinations are of interest, the project scope was a significant undertaking, both in terms of budget and time, with the options selected. The report is one of the technical studies relevant to EPA's ongoing rulemaking efforts, and the scope was designed to support that effort. EPA anticipates that others and perhaps EPA will continue to explore these issues with further studies that add scope.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments		18	The report is lengthy at places, for instance in the description of technologies which users of the simulation software are likely to be already familiar with, while too laconic at other places, e.g. how the selected technologies were modeled in some detail. The draft can benefit from better balancing of its sections. There should also be more words summarizing the illustrative results (e.g., provide ranges of benefits), and assessing them critically (e.g., which technologies seem to incrementally or additively contribute the most), rather than just stating that the results are in Table 7.1 or in Appendix 3. A discussion of uncertainties present in the analysis should be presented so as to enable the reader to place the findings into proper perspective.	The final report addresses some of these comments by adding discussion and examples to some of the modeling-focused sections. However, the results are presented as they were found, without significant discussion of uncertainty or critical assessment. That was the study objective for EPA and the Agency believes that the final report satisfies that objective.	General
Inputs and Parameters		20	The report describes a comprehensive set of engine and vehicle technologies for the prediction of GHG emissions and performance. However, the full range of inputs and parameters is not explicitly presented. It requires the reader to refer to the Data Visualization Tool figures to simulation environment, it is impossible to extract details on, or judge the basis for a number of critical inputs. In some occasions, the report mentions that published data have been used, but there are no references to the source. Baseline engine maps, torque converter maps and shifting maps, electric machine efficiency maps, and control strategies for hybrids, which have very direct effects on vehicle performance and emissions, should be presented in the report, at least in a limited format.	To address this concern, the final report uses public fueling maps concepts, and then illustrates the technical transformation of baseline technologies to the future. See especially revised Sections 4.1 and revised Section 4.2. New Section 4.2.6 provides case studies for EGR DI Turbo and Atkinson engines. The hybrid sections (especially section 6.8) are significantly expanded as well.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		27	Alternative fuels are currently a key research topic and very important for future energy independence. Because usage of these fuels can have an impact on efficiency and emissions, the study would be enhanced if engine performance maps with various fuels were included.	The technology selections and combinations were selected to provide a representative group of combinations that reflect the thinking of the program team of some of the most common expected combinations across the range of light duty classifications. This includes the fuel use. The full slate of options considered is set forth in Attachment A to the final report. While EPA agrees that additional combinations are of interest, the project scope was a significant undertaking, both in terms of budget and time, with the options selected. The report is one of the technical studies relevant to EPA's ongoing rulemaking efforts, and the scope was designed to support that effort. EPA anticipates that others and perhaps EPA will continue to explore these issues with further studies that add scope.	General
Simulation methodology		28	The RSM approach is certainly a good way to provide quick access to wide range of results, but it has the limitation that a large number of assumptions have to be made ahead of time in order to determine the design space. Also, creating these encompassing RSM's requires a significant amount of simulations, and all the results will not necessarily be of interest. If a more flexible model/simulation was created and coupled to a user-friendly interface, users might be able to obtain and analyze the desired results instead of being constrained by the design space previously determined.	The RSM approach was a foundational aspect of this study. While the reviewer's option may provide another valuable approach, no specific report or study change is needed in response to this comment.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology		29	Even though the authors attempt to describe the simulation methodology and assumptions in the report, it lacks details of the models employed, which makes it hard to determine if refinements need to be made, or even if more appropriate models/methods should be used. It is understandable that, due to the proprietary data, it is not possible to present everything. However, without any of this information, the RSM results are more difficult to interpret.	To address this concern, the final report uses public fueling maps concepts, and then illustrates the technical transformation of baseline technologies to the future. See especially revised Sections 4.1 and revised Section 4.2. New Section 4.2.6 provides case studies for EGR DI Turbo and Atkinson engines. The hybrid sections (especially section 6.8) are significantly expanded as well.	General
Results		45	It would be desirable to include a complete test case with the appropriate inputs, analysis and outputs as part of the report. The sample results presented in figures seem to have been included to indicate the RSM and Data Visualization Tool's capabilities, but they do not provide a complete picture from which to draw solid conclusions.	The new user manual for the RSM tool will present a complete test case.	General
Completeness		47	Some of the aspects lacking form the report have already been mentioned and discussed in the relevant sections.	EPA and Ricardo appreciate the comment; no further response is required.	General
Completeness		48	In general, the report provides a fair description of the modeling process. Unfortunately, there are no equations, plots or maps showing any specific modeling item, thus making this part of the report vague.	The final report adds detail to both the technology discussions and the modeling discussions to better articulate the scope and approach of the study.	General
Completeness		49	It might be possible to shorten the descriptions related to the individual technologies implemented and their improvements and add more details on how they have been modeled. People using this tool will most likely not use the brief descriptions of the various technologies to draw conclusions and make decisions.	The final report adds detail to both the technology discussions and the modeling discussions to better articulate the scope and approach of the study.	General
Recommendations		51	Various suggestions have already been included in the relevant sections.	EPA and Ricardo appreciate the comment; no further response is required.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations		52	The authors should expand the modeling sections. In particular, they should cite literature references (where possible) and provide more detail when empirical data, modifiers, or scaling laws are used.	The final report adopts many of these suggestions.	General
Recommendations		53	Flexibility should be added to the models. Some engine technologies, such as variable cam phasing, HCCI and alternative fuels should be considered.	EPA and Ricardo appreciate the comment. Future analyses could expand the scope to include these technologies. VCT and HCCI were incorporated in the previous study.	General
Recommendations		54	A self-contained study should be presented as a test case for the results so that specific conclusions can be drawn and the utility of the approach more easily understood.	The new user manual for the RSM tool will present a complete test case.	General
Inputs and Parameters		72	How were baseline BFSC maps modified? Was it across the board improvement or were improvements only attributed to certain parts of the map?	Baseline BSFC maps were never modified.	General
Simulation methodology		78	Some assessment of the model uncertainty would be helpful. This could be a qualitative rating assigned by the advisory committee or a more rigorous method could be used.	For future consideration in any follow-up work	General
Simulation methodology		79	More detail on the types of models is required. Do some models use first principals of physics and others lumped parameter?	Has be addressed with inclusion of additional EASY5 model description/citations in report	General
Simulation methodology		80	ANOVA or some other analytical approach to consider technology interactions needs to be deployed.	For future consideration in any follow-up work	General
Simulation methodology		81	It says a statistical analysis was used to correlate variations in the input factors to variations in the output factors. This is ambiguous. What analysis method was used? Where is it reported? I didn't see anything in the results about this. It was used to generate the RSM, but what was the measure of fitment? How did the RSM fit compare from vehicle config to vehicle config.	Has be addressed with revisions to Section 3.4 of report	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness		148	When it comes to GHG reductions why weren't plug-in hybrids considered?	GHG reductions for PHEVs are calculated by applying a utility factor (percentage of BEV) to the results of this study for the appropriate hybrid vehicle.	General
Recommendations		149	Instead of using proprietary Ricardo data/models/control algorithms citable data should be used.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them.	General
Recommendations		150	Without stating how this model is going to be used in the regulatory decision making process, it is very difficult to assess its appropriateness.	The following EPA documentation in support of the 2017-2025 rule is relevant to responding to this comment: Chapter 3 of the Joint Technical Support Document, and Chapter 2 of the EPA's Regulatory Impact Analysis.	General
Recommendations		152	Guidelines for appropriate use should be given.	The new user manual for the RSM tool will present instructions for use and a complete test case.	General
Recommendations		155	In terms of acceptable use: rather that trying to use the model to assess the boundaries of the envelope (or which technology is better), the tool could be used to find the areas of maximum overlap. In other words, knowing that the same performance and fuel economy is achievable using different technologies lends more confidence that the result is achievable. Theoretically this number could be a calculated value generated from the RSM's.	EPA and Ricardo appreciate the comment; no response needed.	General
Recommendations		156	Recommend allowing "real world" drive cycles to assess the robustness of the results. Could be a user generated result from a composite of the data sets already generated.	EPA and Ricardo appreciate the comment; no response needed.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations		157	Should define the process for data selection….eventually you'll be asked by a manufacturer, 'how do we get 'x' technology included for consideration in the study.	EPA and Ricardo appreciate the comment; no response needed.	General
Other Comments		159	Having conducted a similar effort for USCAR on the PNGV program, I understand that considerable effort is required to develop such a model. I don't want to diminish all the hard work that was done, by only offering criticism in the above sections. It appears that the intent of the approach to this activity is in the right place, just better documentation is needed and appropriate use guidelines.	EPA and Ricardo appreciate the comment; no further response is required.	General
Inputs and Parameters	Baseline vehicle subsystem models/maps	161	The models/maps for the subsystems used in these vehicle models were not provided in the report so that their adequacy could not be assessed.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them. Also, on specific maps relevant to the engine model, we note that the effects of the valve actuation system, fueling system, and boost system were integrated into the final torque curves and fueling maps, therefore subsystem performance maps, such as turbine and compressor efficiency maps, are not relevant to this study.	General
Inputs and Parameters	Baseline vehicle subsystem models/maps	162	Including these baseline models in the report would assist in assessing the development process as well as the adequacy of the new technology subsystem models/maps, which was not possible in this peer review.	See response to Comment Excerpt 161.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters	Engine technology selection	169	Issue: The technology "package definitions" precluded an examination of the individual effects of a variety of technologies such as a single stage turbocharger vs. series-sequential turbochargers.	EPA and Ricardo acknowledge this limitation. As with any study, there is a need to balance the ability to evaluate each variable, with the ability to contain the study to a manageable scope. Ricardo subject matter experts determined the type of turbochargers used in the study.	General
Inputs and Parameters		181	None of the subsystem models/maps were provided for review so comments on their adequacy are not possible.	See response to Comment Excerpt 161.	General
Inputs and Parameters		182	Issue: Insufficient reasons are presented to justify why the models/maps for subsystems are not provided in the report, especially when one of the goals of the report was to provide transparency (per Jeff Cherry, May 5, 2011 teleconference and Item 5, below).	See response to Comment Excerpt 161.	General
Inputs and Parameters		184	Recommendation: To establish the adequacy of the subsystem models/maps, derivation details should be provided.	See response to Comment Excerpt 161.	General
Simulation methodology		198	Concern: Methodologies used in simulating the subsystems and the overall vehicles were not provided, so that the validity and applicability of these methodologies cannot be assessed.	See response to Comment Excerpt 161.	General
Simulation methodology	Major deficiencies in the report	200	Technical descriptions of how the subsystems and vehicle models/maps for the baseline vehicles were developed were not provided.	See response to Comment Excerpt 161.	General
Simulation methodology	Major deficiencies in the report	201	Most importantly, only non-technical descriptions of how each of the advanced technology subsystem models/maps was developed were provided.	See response to Comment Excerpt 161.	General
Simulation methodology	Major deficiencies in the report	203	Descriptions of how synergistic effects were handled were not provided.	Synergistic effects are inherent to the proprietary Ricardo vehicle models.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Results	Overview of results	211	The results from this work could be useful in evaluating possible GHG emission reductions in the 2020-2025 timeframe if the issues throughout this peer review were addressed and the recommendations in Item 5 (below) were implemented. However, even if the foregoing deficiencies were resolved, the foregoing caveat that there are numerous technologies that have potential for reduced GHG emissions that were not included in this study must be recognized (see Item 1B, above).	EPA believes that the overall revisions in the final report address the core concerns raised by the reviewers during the peer review. EPA agrees that other technologies could also reduce GHG emissions (see the full set of technologies considered in Attachment A to the final report), but also must develop study boundaries that enable a report such as this one to focus on specific options within the confines of a cost-effective study design.	General
Results	Sample runs of CSM	212	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Baseline engine with AT6-2010 to Stoichiometric DI Turbo, Stop-Start, AT8-2020 - 38.7% improvement in M-H mpg - Lumsden et al. (2009) identified a 25-30% improvement in mpg for a 50% downsized, DI, Turbo engine. - The remaining 9-14% potentially could be explained by stop-start and the change from AT6-2010 to AT8-2020 (although the details of the systems and the models used would be needed to make this assessment).	Baseline engines cannot be combined with advanced technologies in the RSM tool; the RSM tool has been modified to prevent this issue.	General
Results	Sample runs of CSM	213	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: AT8-2020 to DCT - 3.3% improvement in M-H mpg - This improvement appears reasonable.	EPA and Ricardo appreciate the comment; no further response is required.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Results	Sample runs of CSM	214	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Stoichiometric DI Turbo with Stop-Start to P2 Hybrid - 18.2% improvement in M-H mpg - This improvement appears reasonable.	EPA and Ricardo appreciate the comment; no further response is required.	General
Results	Issue with CSM	219	Some examples where the model did not allow a buildup of comparison cases are: - Baseline engine with AT-2010 to AT-2020 to DCT - Baseline engine without stop-start to with/stop-start	Baseline engines cannot be combined with advanced technologies in the RSM tool; the RSM tool has been modified to prevent this issue.	General
Results	Other issues	222	When the baseline cases were run in the Complex Systems Model, incorrect values of displacement and architecture were shown in the output. - As an example shown on the attached chart (copied from the output of the CSM), the baseline for the Standard Car with a 2.4L engine shows a displacement of 1.04L. - For the same example, the architecture is shown as “conventional SS”, whereas the baseline was understood to not have the stop-start feature (page 22, Table 5-2).	Baseline engines cannot be combined with advanced technologies in the RSM tool; the RSM tool has been modified to prevent this issue.	General
Completeness		224	An overall schematic and description of the powertrain and vehicle models and the associated subsystem models/maps were not provided. Only vague descriptions were included in the text of the report.	See Figure 6.1 in the final report, as well as the numerous changes made to provide further detail on these types of issues throughout the report.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness		225	Technical descriptions of how the subsystems and vehicle models/maps for the baseline vehicles were developed were not provided.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of the modeling and related issues, and how the study addressed them.	General
Completeness		226	None of the overall or subsystem models/maps were provided for review so comments on their adequacy are not possible.	See response to Comment Excerpt 225.	General
Completeness		227	Most importantly, only minimal descriptions were provided of how each of the advanced technology subsystem models/maps was developed.	See response to Comment Excerpt 225.	General
Completeness		228	Descriptions of the algorithms used for engine control, transmission control, hybrid system control, and accessory control were not provided.	See response to Comment Excerpt 225.	General
Completeness		229	Descriptions of how synergistic effects were handled were not provided.	The synergistic effects are inherent in the Ricardo proprietary vehicle models.	General
Recommendations		231	This report needs major enhancements to reach the stated goal of being open and transparent in the assumptions made and the methods of simulation. Recommendations to rectify the deficiencies in these areas are provided in the previous four items.	See response to Comment Excerpt 225.	General
Recommendations	Overall recommendations	232	Overall Recommendation: Provide all vehicle and powertrain models/maps and subsystem models/maps used in the analysis in the report so that they can be critically reviewed.	See response to Comment Excerpt 161.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	Overall recommendations	233	Overall Recommendation: Expand the technology "package definitions" to enable evaluation of the individual effects of a variety of technologies.	The technology selections and combinations were selected to provide a representative group of combinations that reflect the thinking of the program team of some of the most common expected combinations across the range of light duty classifications. The full slate of options considered is set forth in Attachment A to the final report. In addition, while the use of proprietary data was a fundamental element of the study design, Ricardo has added significant details and graphics, including a number of publically available reference materials, to increase the transparency and overall utility of the final report. While EPA agrees that additional combinations are of interest, the project scope was a significant undertaking, both in terms of budget and time, with the options selected. The report is one of the technical studies relevant to EPA's ongoing rulemaking efforts, and the scope was designed to support that effort. EPA anticipates that others and perhaps EPA will continue to explore these issues with further studies that add scope.	General
Recommendations	Specific recommendations for improvements	235	Provide technical descriptions of how the subsystems and vehicle models/maps for the baseline vehicles were developed.	See response to Comment Excerpt 225.	General
Recommendations	Specific recommendations for improvements	236	Provide overall system and subsystem models/maps in the report.	See response to Comment Excerpt 225.	General
Recommendations	Specific recommendations for improvements	237	Provide detailed technical descriptions of how each of the advanced technology subsystem models/maps was developed.	See response to Comment Excerpt 225.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	Specific recommendations for improvements	239	Provide detailed descriptions of how synergistic effects were handled.	This is inherent to Ricardo's proprietary vehicle models.	General
Recommendations		243	Recommendation: Subsystem models/map should be added to this report and another peer review conducted to assess their adequacy before this report is released.	See response to Comment Excerpt 225.	General
Other Comments		248	The vehicle model and powertrain model were developed and implemented by Ricardo in the MSC.Easy5 software package. The model reacts to driver input to provide the torque levels and wheel speeds required to drive a specified vehicle over specified driving cycles. The overall model consists of subsystem models that determine key component outputs such as torque, speeds, heat rejection, and efficiencies. Subsystem models are expected to be required for the engine, accessories, transmission, hybrid system (if included), final drive, tires and vehicle, although the report did not clearly specify the individual subsystem models used.	See response to Comment Excerpt 225.	General
Other Comments		249	A design of experiments (DOE) matrix was constructed and the vehicle models were used to generate selected performance, fuel economy and GHG emission results over the design space of the DOE matrix. Response surface modeling (RSM) was generated in the form of neural networks. The output from each model simulation run was used to develop the main output factors used in the fit of the RSM. The resulting Complex Systems Model (CSM) provides a useful tool for viewing the results from this analysis that included over 350,000 individual vehicle simulation cases.	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments		250	The vehicle and powertrain models/maps and subsystem models/maps used in the analysis were not provided in the report and could not be reviewed. In most cases, the report stated that the models/maps were either proprietary to Ricardo or at least elements were proprietary so that they could not be provided for review. Without having these models/maps and subsystem models/maps, their adequacy and suitability cannot be assessed.	See response to Comment Excerpt 225.	General
Other Comments		251	Overall Recommendation: Provide all vehicle and powertrain models/maps and subsystem models/maps used in the analysis in the report so that they can be critically reviewed.	See response to Comment Excerpt 225.	General
Other Comments		252	The technology "package definitions" preclude an examination of the individual effects of a variety of technologies. For example, for the Stoichiometric DI Turbo engine, only the version with a series-sequential turbocharger could be evaluated whereas a lower cost alternative with a single turbocharger could not be evaluated. Likewise, only the AT8-2020 transmission could be evaluated with the Stoichiometric DI Turbo engine, while the substitution of the AT6-2010, as a lower cost alternative, could not be evaluated.	See response to Comment Excerpt 233.	General
Other Comments		253	Overall Recommendation: Expand the technology "package definitions" to enable evaluation of the individual effects of a variety of technologies.	See response to Comment Excerpt 252.	General
Other Comments		291	Sample Output From Complex System Model (CSM) 5/4/2011 Relative Percentage Differences Were Added by W. R. Wade (see Exhibit 9)	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	General
References Used	References (Used for this Review that are also listed in the Report)	293	Reference that summarizes the 2008 study by Perrin Quarles Associates (PQA) that provided the 2010 baseline cases for five LDV classes (Page 30 of the report): 4. PQA and Ricardo (2008), "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies"	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Executive Summary		295	For the purpose of describing the modeling approach used in the forecasting of the performance of future technologies, the report reviewed is inadequate. In virtually every area, the report lacks sufficient information to answer the charge questions provided for the reviewer. It is entirely possible that the approach used is satisfactory for the intended purpose. However, given the information provided for the review, it is not possible for this reviewer to make any statement regarding the suitability of this approach.	See response to Comment Excerpt 225.	General
Inputs and Parameters		296	From a high level, it is clear what the inputs to the design space tool are, which are listed in tables 8.1 and 8.2. At the next level down (i.e. the vehicle and subsystem models) there is no comprehensive handling of inputs in parameters in the report. Some models are partially fleshed out in this area but most are lacking. By way of example, the engine models are described as maps which are "defined by their torque curve, fueling map, and other input parameters" where "other input parameters" are never defined.	See response to Comment Excerpt 225.	General
Results		298	The third charge questions deals with the validity and the applicability of the resulting prediction. The difficulty in this task is that it is an extrapolation from present technology that uses an extrapolation method (i.e. the model) and a set of inputs to the model (i.e. future powertrain data.) Since it is not possible to validate the results against vehicles and technology that do not exist, one can only ensure that the model and the model inputs are appropriate for the task. Because of the lack of transparency in the model and inputs it is difficult to make any claims regarding the results. In trying to validate results, one example is cited in the body of the report that shows the baseline engine getting superior HWFET and US06 fuel economy than all of the other non-HEV powertrains with other factors being the same – this leaves some skepticism regarding the results.	The advanced turbo engines, when heavily downsized, operates outside of the most optimum range on the more demanding drive cycles (such as the US06). Likewise, naturally aspirated engines tend to have their best efficiency at high load conditions (cf. Figure 4.10)	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations		300	Given the low level of detail given in the report, it does seem that the strategy used is consistent with the goal of the work and what others in the field are doing. That being said, the report is inadequate in nearly every respect at documenting model inputs, model parameters, modeling methodology, and the sources and techniques used to develop the technology performance data. Given the need for transparency in this effort, this reviewer feels that the detail in the report is wholly inadequate to document the process used. The organization responsible for the modeling has expertise in this area it is certainly possible that the methodology is sound, however, given just the information in the report there is simply no way for an external reviewer to make this conclusion.	See response to Comment Excerpt 225.	General
Recommendations		301	Because of the lack of hard information to answer the charge questions, this peer review evolved mainly into a suggested list of details that should be brought forward in order to allow the charge questions to be answered properly. With this information, it is hoped that a person with expertise in the appropriate areas will be able comment on the work more fully.	See response to Comment Excerpt 225.	General
Recommendations	Aftertreatment/ Emissions Solutions	316	Provide better evidence that powertrain packages have credible paths to meet emissions standards.	The modeling ground rules state that "2020–2025 vehicles will meet future California LEV III requirements for criteria pollutants, which are assumed to be equivalent to current SULEV II (or EPA Tier 2 Bin 2) levels." These parameters were used in the proprietary Ricardo vehicle models.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations	Aftertreatment/ Emissions Solutions	317	Provide evidence that fuel enrichment strategies are consistent with emissions regulations.	The modeling ground rules state that "2020–2025 vehicles will meet future California LEV III requirements for criteria pollutants, which are assumed to be equivalent to current SULEV II (or EPA Tier 2 Bin 2) levels." These parameters were used in the proprietary Ricardo vehicle models. No enrichment was used in the development of any of the boosted engines, following data from Mahle.	General
Recommendations	Hybrid technology selection	351	Validate that other vehicle performance metrics, like emissions and acceleration, are not adversely impacted by an algorithm that focuses solely on fuel economy. The emission side of things will challenge to validate with this level of model, however, some kind of assurance should be made to these factors which are currently not addressed at all.	The ground rules for the project state that all simulations meet Tier 2 Bin 2 emissions. Performance metrics were held constant for all vehicles.	General
Simulation methodology		370	Provide error metrics for the neural network RSMs (i.e. R2, min absolute error, max absolute error, error histograms, error standard deviation, etc.) before combining the fit and validation data sets.	Methodology was to fit the RSM using two-thirds of the available data and test the RSM using the remaining data. Fits were within acceptable limits (3-5%).	General
Simulation methodology		371	Provide the error metrics described above for the RSMs after combining the fit and validation data sets.	See response to Comment Excerpt 370.	General
Simulation methodology		372	Provide validation that the data analysis tool correctly uses the RSM to predict results very close to the source data (i.e. demonstrate the GUI software behaves as expected).	The RSM fit quality is represented by the R2 values. The predicted data was checked against the source data to ensure good predictability.	General
Results		373	As outlined in the executive summary, it was not possible to answer the charge questions provided for this peer review due to lack of completeness in the report. Thus, this report was aimed at providing feedback on what information would be helpful to allow a reviewer to truly evaluate the spirit of the charge questions. With the above in mind, the following conclusions are made.	In the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them.	General

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Results		374	The modeling approach describe in the report could be appropriate for the simulation task required and is generally consistent with approaches used by other groups in this field. The conclusions from the report could very well be sound; however, there is insufficient information and validation provided in the report to determine if this is the case. The technique used to analyze the mass simulation runs could also be sound, although the accuracy of the response surface model is not cited in the report.	See response to Comment Excerpt 373.	General
Results		375	The process of arriving at the performance of the future technologies is not well described.	See response to Comment Excerpt 373.	General
Results		376	The majority of models are only described qualitatively making it hard or impossible to judge the soundness of the model.	See response to Comment Excerpt 373.	General
Results		377	Some of the qualitative descriptions of the models indicate that models do not consider some important factors.	See response to Comment Excerpt 373.	General
Results		378	Because of the qualitative nature of the model descriptions, there is a major lack of transparency in the inputs and parameters in the models.	See response to Comment Excerpt 373.	General
Results		379	Where precise value(s) are given for parameters in the model, the report generally does not cite the source of the value(s) or provide validation of the particular value.	See response to Comment Excerpt 373.	General
Results		380	Validation of the model and sub-models is not satisfactory (It is acknowledged that many of these technologies do not exist, but the parameters and structure of the model have to be based on something.)	See response to Comment Excerpt 373.	General

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Executive Summary		383	The supplemental review material provided some answers to questions posed above, but in general, did not provide the level of detail necessary to ensure a thorough review of the process. The conclusion of this reviewer remains similar as on the original review, which is that there were no serious flaws found in the work, however, there were enough omissions that it is not possible to accurately judge if the predictions made are accurate. The biggest concern in this work is the lack of validation and/or citation of where data and models are coming from. There are numerous maps that are presented in the follow-up material, however, these maps had to have originated from some process (which needs documented) and should be compared against some kind of validation. Despite the lack of documentation provided, the work is generally that of a project team that is competent in this field of study.	See response to Comment Excerpt 373.	General
Inputs and Parameters	SI Engine Maps and Diesel Engine Maps	394	The baseline engine map data is shown in a series of figures and references are provided for the specific vehicle that the map is for. It is assumed that this indicates that this data has been measured experimentally. If this is the case, then this is well documented.	EPA and Ricardo appreciate the comment; no further response is required.	General
Inputs and Parameters		407	Curious about why no discussion of advanced materials in engines to achieve improvements.	Advanced materials were considered only to the extent that they facilitated other improvements, such as in friction or mass. The benefits of advanced materials were not explicitly considered separately from other technologies.	General
Inputs and Parameters		409	Future Developments in Engine Friction – I think it would be worthwhile to point out that there are technologies that are more driven by increased durability rather than fuel economy but they could play off one another. Engine friction reduction is one of those areas.	EPA and Ricardo acknowledge and appreciate the reviewer's comments.	General

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Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Simulation methodology		414	EHVA: The paper addresses the potential of the technology nicely. Since it was published in 2003 has any more recent work been done to address the durability and issues brought up in the conclusions?	Durability is beyond the scope of this study.	General
Results		417	After reading the papers and presentations I come to the assumption that the papers were used to guide the selection of technology, but it's not clear which maps were generated from model and which maps were generated in the test cell. It's evident that there is a heavy concentration on engine technology and the fidelity of the engine models, which is appropriate. I have a slight concern about the impression I'm left with; that there is not much attention to the interaction of systems effects. This is most likely because of cost and availability of data. I would like to see the EPA articulate a process for looking at system interactions, continuous improvement and model compatibility. For example if the study were to run over several years the researches should feel confident comparing a result generated with the models in 2013 to modeling results generated today.	All of the advanced engine maps used in the models were generated using Ricardo experience with engine design and engine dynamometer test results from experimental engines and are meant to represent a specific engine calibration. The engine maps contain fuel mass flow rates based on engine speed and load. Any vehicle system or interactions of several systems that would reduce the powertrain work required are accounted for in the models by operating the engine at the reduced speed or load.	General
Completeness		418	Hybrid: Ricardo asserts that electric machine design activities of the future will most like concentrate around cost reductions; however I see machine efficiency dropping in order to meet cost reductions. Therefore I think it premature to assume that efficiency will stay the same and cost will drop.	Please refer to EPA's 2017-2025 rule (Chapter 3 of the joint TSD) to reference how electric component efficiency and costs are handled by the agencies.	General
Inputs and Parameters		419	Ricardo, Action Item Response, 16 Feb 10, 15 p. (proprietary): A response to an EPA inquiry, this document deals with engine maps, engine map comparisons, engine map plots, transmissions, batteries, motor and generator efficiency maps. Comment: Ricardo responses and data selection seem reasonable.	EPA and Ricardo appreciate the comment; no response needed.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		420	Ricardo, Baseline Camry with Alternator Regen and Shift Optimizer Development of Optimized Shifting Strategy Light Duty Vehicle Complex Systems Simulation EPA Contract No. EP-W-07-064, work assignment 2-2, 15 Apr 10, 10 p. (proprietary): This document provides data on effectiveness of shift optimizer, including alternator regen, over the FTP and HWFET. Comment: Seems reasonable, improvements are greater on FTP than HWFET.	EPA and Ricardo appreciate the comment; no response needed.	General
Recommendations		423	Ricardo, BSFC Map Commparisons, LBDI vs EGR Boost & DVA for STDI, OBDI, & EGR Boost, Light Duty Vehicle Complex Systems Simulation, EPA Contract No. EP-W=07=064, work assignment 2-2, 24 Feb 10, 20 p. (proprietary) Comparison of engine technologies in terms of maps of percent difference in bsfc in bmep vs rpm space allows visualization Comment: Straight forward data analysis, presumably as requested by USEPA. Should aid in understanding technology performance differences.	EPA and Ricardo appreciate the comment; no response needed.	General
Inputs and Parameters		424	Mischker, K. and Denger, D., Requirements of a Fully Variable Valvetrain and implementation using the Electro-Hydraulic Valve Control System EHVS, 24th International Vienna Engine Symposium 2003, 17 p. This paper describes an electro-hydraulic valve system (EVHS) and limited data on reduction in bsfc. Comment: This would seem to be of limited quantitative value since technology is well advanced beyond 2003.	EPA and Ricardo appreciate the comment; no response needed. Background materials included both highly relevant data and sources as well as some general information sources used during the course of the study. Not all sources reviewed were of critical importance to the study.	General
Recommendations		426	Ricardo, Response to EPA Questions on the Diesel Engine Fuel Maps, Supplemental Graphs for Word Document, 16 Feb 10, 11 p. (proprietary) Document presents proposed diesel engine maps for MY2020+ vehicles. Comment: Anticipated technologies are listed but how the maps were generated is not described. Maps seem reasonable.	EPA and Ricardo appreciate the comment; no response needed.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness		427	Ricardo, Assessment of Technology Options, Technologies related to Diesel Engines, 23 Nov 09, 17 p. Overview predicts continuation of low uptake in the U.S. LDA and LDT markets. Review deals with various engine technologies to improve efficiency. Individual improvements <1-5%. Most promising is electric turbo-compounding (bottoming cycle to recover exhaust thermal energy to produce electricity). Comment: Individual technology assessments seem reasonable. There is no analysis of integrating several technologies.	EPA and Ricardo appreciate the comment; no response needed.	General
Inputs and Parameters		428	Ricardo, EBDI Project Overview, Ethanol Boosted Direct Injection, Nov 09, 8 p. This study examines ethanol boosted direct injection (EBDI) to optimize engine operation of E85 fuel. Possibility exists to match or exceed diesel performance and reduce CO2 emissions. Comment: It is not clear if comparison of EBDI and diesel is a equal technology level.	See response to Comment Excerpt 424.	General
Inputs and Parameters		430	UOM, HiTor® for elecgtric, hybrid electric, and fuel cell powered vehicles, 18 Aug 09, based on test data map, 5 p. Describes power electronics for motor generator control, including an efficiency map for combined controller and motor based on test data. Comment: Efficiency maps seem reasonable.	EPA and Ricardo appreciate the comment.	General
Recommendations		431	Odvarka, E., et al., Electgric motor--generator for a hybrid electric vehicle, Engineering Mechanics, 16, 131--139, 2009, 9 p. Describes electrical machine options of hybrid electric vehicles. Includes efficiency maps for four technologies. Comment: Data are of general interest, but date from 2003.	See response to Comment Excerpt 424.	General
Inputs and Parameters		432	UOM, PowerPhase®75 for electric, hybrid electric, and fuel cell powered vehicles, not dated, 6 p. Described power electronics of vehicle electric power. Comment: Similar to earlier brochure on power electronics, including efficiency map.	See response to Comment Excerpt 424.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness		433	Ricardo, Future Engine Friction Assessment—Response to Action Item Question SI Engine #4, 18 Feb 11, 4 p. (proprietary) Projects continued reduction in engine friction, 2010--2020. Comment: Data provide confirm projection.	EPA and Ricardo appreciate the comment; no response needed.	General
Completeness		434	Ricardo, Revised Follow--up Answers to 8 April 2010 Meeting with EPA and Ricardo, 19 Apr 10, 8 p. (proprietary) Presents fueling maps for several technologies. Comment: Adds to documentation of engine map data.	EPA and Ricardo appreciate the comment; no response needed.	General
Completeness		435	Alger, T., Southwest Research Institute, Examples of HEDGE Engines, 2009, 4 p. Presents engine map for a 2.4 L I4 High--Efficiency Dilute Gasoline Engine (HEDGE) engine and compares with TC GDI engine, diesel engine. Comment: Adds to documentation of engine map data.	EPA and Ricardo appreciate the comment; no response needed.	General
Completeness		436	Ricardo, Hybrid Controls Peer Review, 18 Feb 10, 31 p. (proprietary) Review of hybrid control technologies for various architectures. Review of battery operation in cold weather. Comment: Thorough description of technologies and their operation characteristics. Battery discussion covers similar material to an earlier paper.	EPA and Ricardo appreciate the comment; no response needed.	General
Inputs and Parameters		437	Ricardo, Hybrids Control Strategy, 6 Aug 10, 41 p. (proprietary) Discusses development of control strategies for P2 and Power Split hybrids. Comment: Includes efficiency maps and substantial technical detail including vehicle mass effect.	See response to Comment Excerpt 424.	General
Completeness		438	Ricardo, Simulation Input Data Review, 4 Feb 10, 14 p. (proprietary) Described hybrid architectures with emphasis on machine-inverter combine efficiencies, including efficiency maps. Comment: More data, seems reasonable.	EPA and Ricardo appreciate the comment; no response needed.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		439	Ricardo, Assessment of Technology Options, 18 Nov 09, 14 p. (proprietary) Assessment of hybrid technologies using evaluation template. Comment: Treats a range of hybrid technologies, including series hydraulic, giving projections of CO2 reduction benefits.	EPA and Ricardo appreciate the comment; no response needed.	General
Inputs and Parameters		440	Ricardo, Simulation Input Data Review, 2 Feb 10, 30 p. (proprietary) Document review modeling parameters for vehicle performance simulations, including engine efficiency maps for a range of engine and transmission technologies. Comment: This is the kind of data that we requested. Includes shift strategies. Seems reasonable and well-documented.	EPA and Ricardo appreciate the comment; no response needed.	General
Simulation methodology		441	Trapp, C., et al., Lean boost and NOx—strategies to control nitrogen oxide emissions, (no date), 23 p. Technical paper that describes lean burn direct injection (LBDI) engines, SCR NOx control, and more. Includes some emission control cost data. Comment: Not clear how this related to Ricardo's model development for EPA.	See response to Comment Excerpt 424.	General
Completeness		442	Trapp, C., et al., NOx emission control options for the Lean Boos downsized gasoline engine, (2 Feb 07), 34 p. Paper compares lean NOx trap and selective catalytic reduction technologies. Includes some engine map data for NOx emissions. Includes cost data for aftertreatment. Comment: Good academic paper with useful data. Not clear what or how Ricardo used.	See response to Comment Excerpt 424.	General
Completeness		443	Trap, C., et al., NOx emission control options for the lean boost downsized gasoline engine, (2 Feb 07), 27 p. Paper review international emissions regulation and technologies to meet. Comment: This paper contains some of the same information as the preceding two. Simulated date presented, again for SCR and LNT technologies.	See response to Comment Excerpt 424.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Recommendations		444	Ricardo, Lean/Stoichiometric switching load for 2020 Hybrid Boost Concept, (no date), 2 p. Presents space velocity and fuel maps. Comment: Relevance not clear.	See response to Comment Excerpt 424.	General
Recommendations		445	Ricardo, Proposed Lean/Stoichiometric switching load for hybrid boost concept, 29 Apr 10, 1 p. Identifies proposed lean zone operating region on engine map. Comment: Relevance not clear.	See response to Comment Excerpt 424.	General
Results		446	Lymburner, J.A., et al., Fuel consumption and NOx Trade-offs on a Port-Fuel-Injected SI Gasoline Engine Equipped with a Lean NOx Trap, 4 Aug 09, 20 p. This technical paper examines the trade-off between NOx control and CO2 emissions. Comment: Good work but relevance not clear.	See response to Comment Excerpt 424.	General
Results		447	Lotus(?), (from Kapus, P.E. et al., May 2007), Comparison to other downsized engines This one figure is a partial engine map with context vague. Comment: Significance is not clear.	See response to Comment Excerpt 424.	General
Completeness		448	Turner, J.W.G., et al., Sabre: a cost-effective engine technology combination of high efficiency, high performance and low CO2 emissions, Low Carbon Vehicles, May 09, IMechE Proceedings, 14 p. This paper describes a technology for reducing COs emissions in a downsized engine. The Sabre engine is a collaboration between Lotus Engineering and Continental Automotive Systems. Comment: Limited performance data provided.	See response to Comment Excerpt 424.	General
Inputs and Parameters		449	Ricardo, Conventional Automatic Nominal Results, 16 Mar 10, 17 p. (proprietary) This presentation includes mileage versus 0-60 mph time maps for a range of vehicles (light duty to large truck). Also presented are comparisons of fuel economy for different regulatory test cycles and technologies. Comment: Significance is not clear.	See response to Comment Excerpt 424.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		451	Ricardo, Revised follow-up answers for hybrid action items, 23 Jun 10, 16 p. (proprietary) This report answers questions on electric drive train efficiency, battery characteristics, and available braking energy, and more. Comment: Interesting data, but implication not clear.	See response to Comment Excerpt 424.	General
Completeness		452	Ricardo, Response to questions regarding the generation of the diesel fuel maps for fuel efficiency simulation, 16 Feb 10, 10 p. (proprietary) Paper answers a series of EPA questions on how the diesel fuel maps were generated. Comment: This is relevant information and provides a convincing description of the technical basis for the diesel fuel maps.	EPA and Ricardo appreciate the comment; no response needed.	General
Simulation methodology		453	Ricardo, Scaling Methodology Review, 19 Jan 10, 9 p. This document explains the scaling methodology used in the EASY5 vehicle model. Comment: This description in clear and useful.	EPA and Ricardo appreciate the comment; no response needed.	General
Completeness		454	Ricardo, SCR as an Enabler for Low CO2 Gasoline Applications, no date, 35 p. This presentation describes technology and implementation for exhaust NOx reduction for lean burn gasoline engines. Comment: Comprehensive discussion of technology, but if and how inconcorporated in the model not clear.	See response to Comment Excerpt 424.	General
Completeness		455	Ricardo, Simulation Input Data Review, 18 Mar 10, 17 p. (proprietary) This document reviews the engine maps used in the model. Includes are examples of the baseline maps plus modifications associated with a range of technologies. Data apply to all 7 vehicle classes. Comment: This is the documentation that was missing in the earlier review material. Looks reasonable and is reassuring.	EPA and Ricardo appreciate the comment; no response needed.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments		456	Ricardo, Assessment of Technology Options, 19 Nov 09, 22 p. (confidential) This document reviews and rates a range of spark-ignition adaptable technologies to reduce CO2 emissions. Biofuels are included. Comment: An interesting compendium but some previously reported.	EPA and Ricardo appreciate the comment; no response needed.	General
Completeness		457	Shimizu, R., et al., Analysis of a Lean Burn Combustion Concept for Hybrid Vehicles, 2009, 13 p. A technical paper, this document describes early (1984) and more recent Toyota lean burn engines. Comment: Interesting technical description but no clear if or how used in the Ricardo model.	See response to Comment Excerpt 424.	General
Simulation methodology		458	Takoaka, T., et al., Toyota, Super high efficient gasoline engine for Toyota hybrid system, (no date), 16 p. This paper describes the hybrid system, IC engine interaction that allows increased IC engine efficiency. Comment: Of general interest but application to the model not clear.	See response to Comment Excerpt 424.	General
Inputs and Parameters		459	Ricardo, Assessment of Technology Options, Technologies related to Transmission and Driveline, 19 Nov 09, 21 p. This document described transmission technologies, including timing of their introduction. Comment: Seems reasonable.	EPA and Ricardo appreciate the comment; no response needed.	General
Recommendations		460	Ricardo, Transient Performance of Advanced Turbocharged Engines, 15 Sep 10, 19 p. (proprietary) This report reviews expected advances in boosting technologies and anticipated effects on vehicle performance. Comment: Interesting information but how it impacts model is not clear.	See response to Comment Excerpt 424.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Completeness		461	Kapus, P., Potential of VVA Systems for Improvement of CO2 Pollutant Emission and Performance of Combustion Engines, 30 Nov 2006, 9 p. This is a technical paper describing variable valve actuation approaches and performance effects. Comment: Useful general technical information.	EPA and Ricardo appreciate the comment; no response needed.	General
Inputs and Parameters		462	Ricardo, Assessment of Technology Options, Technologies related to Vehicle-level Systems, 24 Nov 09, 16 p. This review of vehicle technologies that can improve vehicle efficiencies provides a basic description and information on expected levels of CO2 reduction. Comment: This is a clear description of anticipated improvements in vehicle technologies that reduce load and fuel consumption.	EPA and Ricardo appreciate the comment; no response needed.	General
Executive Summary		463	Ricardo has provided material, which is stated to be the data incorporated in the computer simulation. These data are consistent with the data expected to be the basis of the simulation. It is impossible to establish a precise correspondence between the data and the model. The performance data covered by the 44 separate documents seem reasonable and provide additional assurance that the simulation is soundly based on measured performance. There is no reason to doubt either the integrity or capability of Ricardo in their incorporation of appropriate data into their simulation model.	EPA and Ricardo appreciate the comment; no response needed.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Other Comments		17	For the most part, the right technologies are being considered. However, certain promising technologies and fuel options for IC engine technologies (other than gasoline and diesel) that can make a significant contribution to the improvement of mpg and reduction of CO2 emissions have not been considered, or even mentioned at all. Primary examples are advanced combustion technologies, such as high pressure, dilute burn, low temperature combustion (e.g., Homogeneous Charge Compression Ignition, Partially Premixed Compression Ignition, Spark-Assisted Compression Ignition), and closed-loop, in-cylinder pressure feedback. Some of these combustion technologies have the potential to improve fuel economy by up to 25%. Another significant assumption is that fuels used are equivalent to either 87 octane pump gasoline or 40 cetane pump diesel. However, advanced biofuels, particularly from cellulosic or lingo-cellulosic bio-refinery processes, which from the standpoint of a life cycle analysis have strong potential for reduction of CO2 emissions, can have significantly different properties (including octane and cetane numbers) and combustion characteristics than the current fuels. Note that over 13 billion gallons of renewables were used in 2010, primarily from corn-ethanol and some biodiesel. According to the Renewable Fuel Standard, 36 billion gallons of renewables need to be used by 2022. Also, a joint study carried-out by Sandia and General Motors has shown that ninety billion gallons of ethanol (the energy equivalent of approximately 60 billion gallons of gasoline) can be produced in the US by year 2030 under an aggressive biofuels deployment schedule.	The technology selections and combinations were selected to provide a representative group of combinations that reflect the thinking of the program team of some of the most common expected combinations across the range of light duty classifications. The full slate of options considered is set forth in Attachment A to the final report. While EPA agrees that additional combinations are of interest, the project scope was a significant undertaking, both in terms of budget and time, with the options selected. The report is one of the technical studies relevant to EPA's ongoing rulemaking efforts, and the scope was designed to support that effort. EPA anticipates that others and perhaps EPA will continue to explore these issues with further studies that add scope.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Inputs and Parameters		183	Recommendation: Subsystem models/map should be added to this report and another peer review conducted to assess their adequacy before this report is released.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of these issues and how the study addressed them. Also, on specific maps relevant to the engine model, we note that the effects of the valve actuation system, fueling system, and boost system were integrated into the final torque curves and fueling maps, therefore subsystem performance maps, such as turbine and compressor efficiency maps, are not relevant to this study.	General
Completeness		223	Concern: This report has significant deficiencies in its description of the entire process used in the modeling work. Many of these deficiencies have been previously discussed, but are listed here for completeness.	Use of proprietary data was a ground rule of the study. However, in the final report, we have added a great deal of detail using publically available references and sources to provide further understanding of the modeling and related issues, and how the study addressed them.	General
Completeness	Section 2 Objectives	122	A discussion of appropriate/anticipated use of the results is required.	Please refer to the 2017-2025 rule documents: Chapter 2 of the Joint TSD and Chapter 1 of EPA's draft Regulatory Impact Analysis.	General
Inputs and Parameters	Engine Models	309	This reviewer took some time to look at the data via the tool provided. One table is shown in Figure 1 which shows some unexpected results. The results are for a small car with the dry clutch transmission and it shows the baseline engine having superior fuel economy over all other non-hybrid powertrain options. This is unexpected behavior and, since there is minimal transparency in the model, it cannot be investigated any further. (See Exhibit 10)	The baseline engine may not be selected with advanced technologies. The tool has been corrected to avoid this issue.	General

Table 1: Response to Individual Peer Review Comments

Charge Question Topic	Specific Assumption/ Topic	Comment Excerpt No.	Comment	Response	Report Section Reference
Results		117	On the performance runs, a few tenths of a second represent measurable difference in engine torque for example.	EPA and Ricardo appreciate the comment.	General

References

Coltman, et al. (2008), “Project Sabre: A Close-Spaced Direct Injection 3-Cylinder Engine with Synergistic Technologies to Achieve Low CO2 Output”, SAE Paper 2008-01-0138.

Hellenbroich, et al. (2009), "FEV's New Parallel Hybrid Transmission with Single Dry Clutch and Electric Torque Support."

Lumsden, et al. (2009), “Development of a Turbocharged Direct Injection Downsizing Demonstrator Engine”, SAE Paper 2009-01-1503.

PQA and Ricardo (2008), "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies."

Staunton, et al. (2006), "Evaluation of 2004 Toyota Prius Hybrid Electric Drive System", ORNL technical report TM-2006/423.

Turner, et al. (2009), ‘Sabre: A Cost-Effective Engine Technology Combination for High Efficiency, High Performance and Low CO2 Emissions”, IMechE conference proceedings.

Supplement

Peer Review of
Ricardo, Inc. Draft Report, "Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe"

Final Report

September 30, 2011

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This report was prepared by ICF International for the U.S. Environmental Protection Agency (EPA), Office of Transportation and Air Quality under EPA Contract No. EP-C-06-094, Work Assignment 4-04, at the direction of EPA Work Assignment Manager Jeff Cherry.

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1. Introduction

As the U.S. Environmental Protection Agency (EPA) develops programs to reduce greenhouse gas (GHG) emissions and increase fuel economy of light-duty highway vehicles, there is a need to evaluate the costs of technologies necessary to bring about such improvements. Some potential technology paths that manufacturers might pursue to meet future standards may include advanced engines, hybrid electric systems, and mass reduction, along with additional road load reductions and accessory improvements. One method of assessing the effectiveness of future light duty vehicle (LDV) technologies on future vehicle performance and GHG emissions in the near-term timeframe is through modeling assessments.

Ricardo, Inc. (2011) developed such simulation models and documented the relevant technologies, inputs, modeling techniques, and results of the study in its April 6, 2011, report, *Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020–2025 Timeframe*. Ricardo performed this work under a subcontract to Systems Research and Applications Corporation (SRA) under EPA contract EP-W-07-064. The report documented both LDV technologies likely to be available within the specified timeframe and the development of a visualization tool that allows users to evaluate the effectiveness of such technology packages in both reducing GHG emissions and their resulting effect on vehicle performance. The technologies addressed including conventional and hybrid powertrains, transmissions, engine technologies and displacement, final drive ratio, vehicle weight, and rolling resistance were examined for seven light-duty vehicle classes.

EPA contracted with ICF International (ICF) to coordinate an external peer review of the inputs, methodologies, and results described in this report. The review was broad and encouraged reviewers to address the adequacy of the model's inputs and parameters, the simulation methodology, and its predictions as well as the report's completeness and adequacy for the stated goals.

This report documents the peer review process and provides comments by the peer reviewers in a table sorted by charge question topic and subtopics.

2. The Peer Review Process

From March to September 2011, EPA contracted with ICF to coordinate this peer review. ICF coordinated the peer review in compliance with EPA's *Peer Review Handbook* (3rd Edition) (U.S. EPA, 2006).

EPA requested that the peer reviewers represent subject matter expertise in advanced engine technology, hybrid vehicle technology, and vehicle modeling. ICF developed a list of qualified candidates from the following sources: (1) ICF experts in this field with knowledge of industry, academia, and other organizations, and (2) suggestions from EPA staff. ICF identified ten qualified individuals as candidates to participate in the peer review. ICF sent each of these individuals an introductory screening email to describe the needs of the peer review and to gauge the candidate's interest and availability. ICF asked candidates to provide an updated resume or *curriculum vitae* (CV). Several candidate reviewers were unable to participate in the peer review due to previous commitments, and one did not respond. ICF reviewed the responses and evaluated the resumes/CVs of the interested and available individuals for relevant experience and demonstrated expertise in the above areas, as demonstrated by educational degrees attained, research and work experience, publications, awards, and participation in relevant professional societies.

ICF reviewed the interested, available, and qualified candidates with the following concerns in mind. As stated in the EPA's *Peer Review Handbook* (U.S. EPA, 2006), the group of selected peer reviewers should be "sufficiently broad and diverse to fairly represent the relevant scientific and technical perspectives and fields of knowledge; they should represent a balanced range of technically legitimate points of view." As such, ICF selected peer reviewers to provide a complimentary balance of expertise of the above criteria (see **Table 1**). EPA reviewed and approved ICF's slate of candidate peer reviewers.

The following five individuals agreed to participate in the peer review:

1. Dr. Dennis Assanis, University of Michigan
2. Mr. Scott McBroom, Fallbrook Technologies, Inc.
3. Dr. Shawn Midlam-Mohler, The Ohio State University
4. Dr. Robert Sawyer, University of California at Berkeley
5. Mr. Wallace Wade, Ford Motor Company (Retired)

Table 1. Chart of Peer Reviewer Expertise Areas and Affiliation

Peer Reviewers	LDV Technology	Computer Simulations	HEV Technology
D. Assanis, Academic	✓	✓	✓
S. McBroom, Industry	✓	✓	✓
S. Midlam-Mohler, Academic	✓	✓	✓
R. Sawyer, Academic	✓		✓
W. Wade, Industry (Retired)	✓		✓

Prior to distributing the review materials, ICF sent each of the reviewers a conflict of interest (COI) disclosure and certification form to confirm that no real or potential conflicts of interests existed. The disclosure form addressed topics such as employment, investment interests and assets, property interests, research funding, and various other relevant issues. Upon review of each form, ICF determined that each peer reviewer had no COI issues and then executed subcontract agreements with all reviewers.

ICF provided reviewers with the following materials:

- Draft project report by Ricardo (2011);
- The Ricardo Computer Simulation tool;

- The Peer Reviewer Charge to guide their evaluation; and
- A template for the comments organized around the Peer Reviewer charge.

The Peer Reviewer Charge provided peer reviewers with general guidelines for preparing their overall review, with particular emphasis on inputs, methodologies, and results. The charge to peer reviewers is provided in **Appendix A**. The CVs for the reviewers are included in **Appendix B**.

A mid-review teleconference was held on May 5, 2011, to discuss the charge, the purpose of the review, and to answer any outstanding questions the reviewers might have. The call was moderated by ICF and attended by reviewers Dr. Assanis, Mr. McBroom, Dr. Midlam-Mohler, Dr. Sawyer, and Mr. Wade, as well as EPA staff Jeff Cherry, and Ricardo staff who were familiar with the report. During the mid-review teleconference, several reviewers expressed some concerns about the level of detail provided in the report, but no one requested additional information beyond some cited references.

The consensus of the first review was that reviewers needed more information than was provided in the Ricardo report to complete their review.

EPA requested a second round of peer review in which the peer reviewers would be provide more detailed information. Ricardo provided 45 additional PowerPoint presentations and documents, which included more clarity on assumptions, pictures of engine maps, and other pertinent information. ICF contacted all five reviewers for interest and availability for this additional review. However, only three reviewers confirmed their availability, one could not commit to a five-year term of confidentiality, and one did not respond to the inquiry.

Three individuals agreed to participate in the second round of peer review:

1. Mr. Scott McBroom, Fallbrook Technologies, Inc
2. Dr. Shawn Midlam-Mohler, Ohio State University
3. Dr. Robert Sawyer, University of California, Berkeley

ICF executed non-disclosure agreements (NDA) with Mr. McBroom, Dr. Midlam-Mohler, and Dr. Sawyer. Once the NDAs were in place, ICF sent them the 45 additional review documents, plus the reviewer charge and the reviewer charge template.

3. Verbatim Peer Reviewer Comments in Response to Charge Questions

Table 2 presents the verbatim comments received by the subject matter experts. Comments are sorted by charge question and then topic/categories. Cited exhibits and references are provided starting on page 69 and 74, respectively. In addition, **Appendix C** provides the first round of peer reviewer comments as they were submitted by the peer reviewers, and **Appendix D** provides the second round of peer reviewer comments as they were submitted.

Table 2. Sorted, Verbatim Comments from Reviewers

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	6.3 Accessories	73	1	McBroom	I think the assumption that LDT cooling fans will be engine driven is incorrect. The new F150's have electric fans.
Inputs and Parameters	6.4 Transmission Models	76	1	McBroom	no efficiency maps, no description of the efficiency maps. What was efficiency a function of? Typically it's gear ratio, torque and speed.
Inputs and Parameters	Accessory load assumptions	335	1	Midlam-Mohler	The accessory model is divided into electrical and mechanical loads. The electrical sub-model assumes alternator efficiency's of 55% and 70% for the baseline and advanced vehicles respectively. Given the required simplicity of the model, a simple model like this is likely acceptable, however, there is no source described for the alternator efficiencies. The base electrical load of the vehicle is mentioned briefly, however, no numerical values are given for each vehicle class or any type of model described.
Inputs and Parameters	Accessory load assumptions	336	1	Midlam-Mohler	The electrical system also includes an advanced alternator control which allows for increased alternator usage during decelerations for kinetic energy recovery. The control description given is valid but simplistic, but seems to fit the expected level of accuracy required for the purpose. There is an issue regarding with the approach for modeling the battery during this process. When charging the battery at the stated level of 200 amps, the charging efficiency of the battery will be relatively poor. During removal of the energy later, there will once again be an efficiency penalty. There is no description of a low-voltage battery model in the report nor any explicit reference to such charge/discharge efficiencies. Additionally, an arbitrary limit of a 200 amp alternator is defined for all vehicle classes – it is unlikely that a future small car and a future light heavy duty truck will have an alternator with the same rating.
Inputs and Parameters	Accessory load assumptions	337	1	Midlam-Mohler	On the mechanical side, it is assumed that "required accessories" (e.g. engine water pump, engine oil pump) are included in the engine maps. The mechanical loading of a mechanical fan is mentioned but no description of the model which, at a minimum, should be adjusted based on engine speed and engine power.
Inputs and Parameters	Accessory load assumptions	185	1	Wade	The accessory selections listed in Table 5-2 (page 22) appear to be adequate except for the following issue: Belt driven air conditioning for the stop-start powertrain configuration is not acceptable for driver comfort. Electrically driven air conditioning is required for the stop-start powertrain configuration to provide driver comfort for extended idle periods.
Inputs and Parameters	Accessory load assumptions	186	1	Wade	Input values Alternator efficiency was increased from the current level of 55% to 70% to reflect "an improved efficiency design" (page 26 and 27).

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Accessory load assumptions	187	1	Wade	Comment: Justification for the increase in alternator efficiency from 55% to 70% should be added to the report with references provided. Alternator efficiency as a function of speed and load may be more appropriate than a constant value.
Inputs and Parameters	Accessory load assumptions	188	1	Wade	Accessory power requirements were not provided, such as shown in Figure 3-3 PQA and Ricardo (2008), for example.
Inputs and Parameters	Accessory load assumptions	189	1	Wade	Recommendation: Both mechanically driven and electrically driven accessory power requirements should be clearly provided in the report.
Inputs and Parameters	Actual models/maps for subsystems (engine, transmission, hybrid system, accessories, final drive, tires and vehicle)	181	1	Wade	None of the subsystem models/maps were provided for review so comments on their adequacy are not possible.
Inputs and Parameters	Actual models/maps for subsystems (engine, transmission, hybrid system, accessories, final drive, tires and vehicle)	182	1	Wade	Issue: Insufficient reasons are presented to justify why the models/maps for subsystems are not provided in the report, especially when one of the goals of the report was to provide transparency (per Jeff Cherry, May 5, 2011 teleconference and Item 5, below).

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Actual models/maps for subsystems (engine, transmission, hybrid system, accessories, final drive, tires and vehicle)	183	1	Wade	Recommendation: Subsystem models/map should be added to this report and another peer review conducted to assess their adequacy before this report is released.
Inputs and Parameters	Actual models/maps for subsystems (engine, transmission, hybrid system, accessories, final drive, tires and vehicle)	184	1	Wade	Recommendation: To establish the adequacy of the subsystem models/maps, derivation details should be provided.
Inputs and Parameters	Advanced Valvetrains (Section 4.1.1)	318	1	Midlam-Mohler	Two types of advanced valvetrains were included in the study, cam-profile switching and digital valve actuation. Both of these technologies are aimed at reducing pumping losses at part-load. The impact of these technologies is difficult to predict using simplified modeling techniques and typically require consideration of compressible flow and a 1-D analysis at a minimum. Even with an appropriate fidelity model, these systems require significant amounts of optimization in order to determine the best possible performance across the torque-speed plane of the engine. It is unclear how these systems were used to generate accurate engine maps given the level of detail provided in the report.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Aftertreatment/ Emissions Solutions	315	1	Midlam-Mohler	Based on the report, it seems that emissions solutions are assumed to be available for all powertrain technology packages selected. The report discusses this in some qualitative detail in section 4.2.2 with respect to lean-stoichiometric switching. This discussion is somewhat incomplete, in that the way it is written it assumes operating at stoichiometry lowers exhaust gas temperature. In reality, switching from lean to stoichiometric operation at constant load results in higher exhaust gas temperatures. Despite this factual inconsistency, it is indeed generally better to operate a temperature sensitive catalyst hot and stoichiometric or rich rather than hot and lean – so the concept of lean-stoich switching is valid even if the explanation provided is not. Even without this factual inconsistency, some additional discussion of aftertreatment systems would be of benefit given that lean-burn gasoline engines are at present a well-known technology for many years that is still problematic with respect to emissions control. A separate issue is the topic of fuel enrichment for exhaust temperature management which will have an important impact on emissions and, if emissions are excessive, reduce the peak torque available from an engine.
Inputs and Parameters	Alternator Regen Shift Optimizer	385	2	Midlam-Mohler	The alternator regeneration strategy is not well documented. The key system specifications, such as max alternator output and efficiency, are listed as assumptions without a data source for validation. The efficiency of the battery is not mentioned in this nor other presentations that this reviewer has read – battery efficiency for a lead acid battery at high currents is poor, this would have an impact on the recovery of energy. Strategies like this are disruptive to drivability and this issue is not discussed in the presentation.
Inputs and Parameters	Baseline vehicle subsystem models/maps	160	1	Wade	The development of baseline vehicle models with comparison of the model results to available 2010 EPA fuel economy test data was appropriate.
Inputs and Parameters	Baseline vehicle subsystem models/maps	161	1	Wade	The models/maps for the subsystems used in these vehicle models were not provided in the report so that their adequacy could not be assessed.
Inputs and Parameters	Baseline vehicle subsystem models/maps	162	1	Wade	Including these baseline models in the report would assist in assessing the development process as well as the adequacy of the new technology subsystem models/maps, which was not possible in this peer review.
Inputs and Parameters	Baseline vehicle subsystem models/maps	163	1	Wade	Recommendation: Since the baseline vehicles modeled were 2010 production vehicles, the models/maps for the subsystems used in these vehicle models should be included in the report before it is released.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Baseline vehicle subsystem models/maps	164	1	Wade	A major omission was that a baseline model of a hybrid vehicle, which is significantly more complex than the baseline vehicle, was not developed and compared to available EPA fuel economy test data for production hybrid vehicles.
Inputs and Parameters	Baseline vehicle subsystem models/maps	165	1	Wade	Recommendation: A baseline model of a hybrid vehicle should be developed and compared to 2010 EPA fuel economy test data for production hybrid vehicles.
Inputs and Parameters	Battery SOC swing and SOC	190	1	Wade	Although not contained in the report, an email from Jeff Cherry (EPA) on May 5, 2011 revealed that the SOC swing was 30% SOC to 70% SOC or 40% total, which appears to be appropriate.
Inputs and Parameters	Battery SOC swing and SOC	191	1	Wade	Achieving neutral SOC (neither net accumulation or depletion) for hybrid vehicle simulations is appropriate (page 30).
Inputs and Parameters	Battery Warm up 1, Battery Warm up 2	387	2	Midlam-Mohler	The battery model described has the following possible problems: The model is relatively simple – but could potentially work for the application and generally is consistent with the fidelity of the rest of the model.
Inputs and Parameters	Battery Warm up 1, Battery Warm up 3	388	2	Midlam-Mohler	The battery model described has the following possible problems: The model references ambient temperature for heat rejection. Most HEVs pull in cabin air rather than outside air for cooling, thus, this will cause modeling error.
Inputs and Parameters	Battery Warm up 1, Battery Warm up 4	389	2	Midlam-Mohler	The battery model described has the following possible problems: Adjusting the Mbat x Cpbat term by 200% is a red flag that something might be fundamentally wrong with either the model formulation or the data used in the model. There should be minimal errors in the mass estimation of the pack and the specific heats of battery modules can be found in the literature or through testing.
Inputs and Parameters	Battery Warm up 1, Battery Warm up 5	390	2	Midlam-Mohler	The battery model described has the following possible problems: The method of handling battery packs of different classes of vehicles is not described, nor are the actual parameters for these different models disclosed.
Inputs and Parameters	Boosting System (4.1.3 and 6.3)	326	1	Midlam-Mohler	Boosting was applied to many of the different powertrain packages simulated. Beyond stating what maximum BMEP that was achievable, very little is mentioned in how the efficiency of the boosted engines were determined. Among other factors, boosting often creates a need for spark retard which costs efficiency if compression ratio is fixed. These complex issues are tied to combustion which is inherently difficulty to model. This aspect of the engine model is not well documented in the report.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Direct Injection Fuel Systems	322	1	Midlam-Mohler	Because of the availability of research and production data in this area, it is expected that performance from this technology was used to predict performance rather than any type of modeling approach. That being said, the report does not describe where or how this data might have been used to develop the fuel consumption map of the engines simulated nor what data sources were used.
Inputs and Parameters	DOE ranges	192	1	Wade	The following DOE ranges for Baseline and Conventional Stop-Start (page 23) appear to be appropriate, with the exception of Engine Displacement. Since the default for the Stoichiometric DI Turbo engine appears to be greater than 50% reduction in displacement (Standard Car baseline of 2.4L is reduced to 1.04L for the Stoichiometric DI Turbo (page 46)), the opportunity should be provided to start with a displacment near the baseline engine (2.4L) and progressively decrease it to approximatly 50% (1.04L). This would require an Engine Displacement upper range of over 200%. The model should also have the capabilty of increasing the boost pressure as the displacement is reduced. (See Exhibit 1).
Inputs and Parameters	DOE ranges	193	1	Wade	The following DOE ranges for P2 and PS hybrid vehicles (page 24) appear to be appropriate (See Exhibit 2)
Inputs and Parameters	Electric Traction Components	352	1	Midlam-Mohler	The model of electric traction components is not discussed in any detail, as the only mention in the report is that current technology systems were altered by "decreasing losses in the electric machine and power electronics." Given the importance of the electric motor and inverter system in hybrids this is not acceptable.
Inputs and Parameters	Engine Downsizing	329	1	Midlam-Mohler	Engine scaling is used extensively in the report. Basic scaling based on brake mean effective pressure is common in modeling at this level of fidelity, thus, this does not need any special description. However, the report mentions some means of modeling the increased relative heat loss with small displacement engines which is not a standard technique. The model or process used to account for this effect should be explicitly described given that engine size is one of the key parameters in the design space.
Inputs and Parameters	Engine Models	306	1	Midlam-Mohler	The engine model is the most important element in successfully modeling the capability of future vehicles, since it is the responsible for the largest loss of energy. It is also one of the most difficult aspect to predict since it involves many complicated processes (i.e. combustion, compressible flow) which must be considered in parallel with emissions compliance (i.e. in-cylinder formation, catalytic reduction.) Because of this, this sub-model must be viewed with extreme scrutiny in order to ensure quality outputs from the model.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Engine Models	307	1	Midlam-Mohler	The engine models are "defined by their torque curve, fueling map, and other input parameters." This implies that the maps are static representations of fuel consumption versus torque, engine speed, and other unknown input parameters. Generally speaking, representing engine performance in this fashion is consistent with typical practice for this class of modeling. This comment deals only with the representation of the engine performance in simulation, the generation of the data contained within the map is much more challenging.
Inputs and Parameters	Engine Models	308	1	Midlam-Mohler	The report outlines two methods were used to produce engine models. The first method was used for boosted engines and relied upon published data on advanced concept engines which would represent production engines in the 2020-2025 timeframe. The second method was used with Atkinson and diesel engines and somehow extrapolated from current production engines to the 2020-2025 time frame. The description of both of these methods in the report is unsatisfactory. It also fails to address how the various technologies are used to build up to a single engine map for a specific powertrain. Validation, to the extent possible with future technologies, is also lacking in this area.
Inputs and Parameters	Engine Models	309	1	Midlam-Mohler	This reviewer took some time to look at the data via the tool provided. One table is shown in Figure 1 which shows some unexpected results. The results are for a small car with the dry clutch transmission and it shows the baseline engine having superior fuel economy over all other non-hybrid powertrain options. This is unexpected behavior and, since there is minimal transparency in the model, it cannot be investigated any further. (See Exhibit 10)
Inputs and Parameters	Engine technology selection	342	1	Midlam-Mohler	There are a host of different technologies superimposed to create the future powertrain technologies. There is not a clear process described on how this technology "stack-up" is achieved. For instance, an advanced engine technology may allow for greatly improved BMEP. Greatly improved BMEP often comes at the expense of knock limits which are difficult to model even with sophisticated modeling techniques. In this simulation, many layers of powertrain technology are being compounded upon each other which will not simply sum up to the best benefits of all of the technologies – there are simply too many interactions. At the level of modeling described, which are maps which are altered in various unspecified ways; it is not clear how the technology stack-up is captured..
Inputs and Parameters	Engine technology selection	166	1	Wade	The engine technologies selected for this study, listed in Table 5.1 (page 22), are appropriate, but are not all-inclusive of possible future engine technologies.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Engine technology selection	167	1	Wade	Setting the minimum per-cylinder volume at 0.225L and the minimum number of cylinders at 3 is appropriate. However, achieving customer acceptable NVH with 3 cylinder engines continues to be problematic.
Inputs and Parameters	Engine technology selection	168	1	Wade	Issue: The description of the derivation of all of the engine models/maps was insufficient.
Inputs and Parameters	Engine technology selection	169	1	Wade	Issue: The technology "package definitions" precluded an examination of the individual effects of a variety of technologies such as a single stage turbocharger vs. series-sequential turbochargers.
Inputs and Parameters	Engine technology selection	170	1	Wade	Issue: There are many engine technologies that have potential for reduced GHG emissions that were not included in this study, such as:-Single stage turbocharged engines - Diesel hybrids- Biofueled spark ignition and diesel engines- Natural gas fueled engines- Other alternative fuel engines- Charge depleting PHEV and EV
Inputs and Parameters	Engine technology selection	171	1	Wade	The feasibility of the following assumptions for the engines modeled should be re-examined as indicated below: None of the Stoichiometric DI Turbo engines listed as references by Ricardo (2011) limited the turbine inlet temperature to a value as low as the 950C limit in the Ricardo model (Coltman et al., 2008; Turner et al., 2009; Lumsden et al., 2009). Reducing the turbine inlet temperature to reach this limit is expected to result in BMEP levels below the assumed 25-30 bar level in the model (which were obtained in the referenced engine with a turbine inlet temperature of 1025C).
Inputs and Parameters	Engine technology selection	172	1	Wade	The feasibility of the following assumptions for the engines modeled should be re-examined as indicated below: Turbocharger delays of the magnitude assumed in the model will result in significant driveability issues for engines that are downsized approximately 50%. Although Ricardo (2011) assumed a turbocharger delay of approximately 1.5 seconds, the comparable delay published for a research engine was significantly longer at 2.5 seconds (Lumsden et al., 2009).
Inputs and Parameters	Future Friction Assessment	392	2	Midlam-Mohler	The provided presentation does not describe how engine friction projections to 2020 are made or how they are modeled. It provides some data from 1995 to 2005, however, it does not provide any useful insight into how this information is used.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	HEV Battery Model	356	1	Midlam-Mohler	Battery models for HEVs are necessary to adequately model the performance of an HEV. The report provides no substantive description of the battery pack model, other than that the model was developed by "lowering internal resistance in the battery pack to represent 2010 chemistries under development." Battery pack size is also not a currently a factor in the model – this has a impact of charge and discharge efficiency of the battery pack.
Inputs and Parameters	Hybrid technology selection	345	1	Midlam-Mohler	Hybrid vehicles are particularly challenging to model because of the extra components which allow multiple torque sources, and thus, require som form of torque management strategy (i.e. a supervisory control.) The report briefly describes a proprietary supervisory control strategy that is used to optimize the control strategy for the FTP, HWFET, and US06 drive cycle. The strategy claims to provide the "lowest possible fuel consumption" which seems to be somewhat of an exaggeration – this implies optimality which is quite a burden to achieve and verify for such a complicated problem. The strategy also is reported to be "SOC neutral over a drive cycle" which is also difficult to achieve in practice in a forward looking model. Once can get SOC with a certain window, however, short of knowing the future or simply not using the battery - it is impossible to develop a totally SOC neutral control strategy.
Inputs and Parameters	Hybrid technology selection	346	1	Midlam-Mohler	Another factor that must be considered is that a hybrid strategy that achieves maximum fuel efficiency on FTP, HWFET, and US06 does not consider many other relevant factors. Performance metrics like 0-60 time and drivability metrics often suffer in practice. In today's hybrids, the number of stop-start events is sometimes limited from the optimum number for efficiency because of the emissions concerns. Because of these factors and others, a strategy achieving optimal efficiency may be higher than what can be achieved in practice.
Inputs and Parameters	Hybrid technology selection	347	1	Midlam-Mohler	Without even basic details on the hybrid control strategy, it is simply not possible to evaluate this aspect of the work. Because of the batch simulations with varying component sizes and characteristics, this problem is not trivial. Supervisory control strategies used in practice and in the literature require intimate knowledge of the efficiency characteristics and performance characteristics of all of the components (engine, electric motors/inverters, hydraulic braking system, and energy storage system) to develop control algorithms. This concern is amplified by the lack of validation of the hybrid vehicle model against a known production vehicle. It is unclear how a "one-size fits all" control strategy can be truly be perform near optimal over such widely varying vehicle platforms.
Inputs and Parameters	Hybrid technology selection	348	1	Midlam-Mohler	A last comment is that there is no validation of the HEV model against current production vehicles. At a minimum, the Toyota Prius has been dissected sufficiently in the public domain to conduct a validation of this class of hybrid electric vehicle.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Hybrid technology selection	177	1	Wade	The hybrid technologies selected for this study, listed in Table 5.2 (page 22) are appropriate.
Inputs and Parameters	Hybrid technology selection	178	1	Wade	Issue: The adequacy of the P2 Parallel and PS Power Split Hybrid systems cannot be determined without having, at a minimum, schematics and operational characteristics of the each system together with comparisons with today's hybrid systems.
Inputs and Parameters	Hybrid technology selection	179	1	Wade	Although not contained in the report, the teleconference call with Jeff Cherry (EPA) on May 5, 2011 revealed that 90% of the deceleration kinetic energy would be recovered. Kinetic energy recovery is limited by the following: - Maintaining high generator efficiency over the range of speeds and resistive torques encountered during deceleration - Limitations on the rate at which energy can be stored in the battery -Losses in the power electronics -Some energy is lost when energy is withdrawn from the battery for delivery to the motor. - Inefficiencies in the motor at the speeds and torques required. The inefficiencies of each of these four subsystems are in series and are compounded. If each subsystem had 90% efficiency, the kinetic energy recovery efficiency would be only 66%.
Inputs and Parameters	Hybrid technology selection	180	1	Wade	Issue: Capturing 90% of the deceleration kinetic energy is a significantly goal. The technology to be used to achieve this goal needs to be explained and appropriate references added to the report.
Inputs and Parameters	Input Data Review	397	2	Midlam-Mohler	The documentation on the Diesel engine maps was helpful; however, it did not discuss how the 2020 engine maps were developed. This is critical for having confidence in the predictions made for the Diesel powertrains in 2020.
Inputs and Parameters	Input Data Review	398	2	Midlam-Mohler	The shift strategy is discussed qualitatively; however, it is not described in enough detail to understand exactly how it is accomplished. Shift schedules are shown, however, no validation is shown that would indicate that these shift schedules are optimal as claimed.
Inputs and Parameters	Input Data Review	399	2	Midlam-Mohler	The torque converter models are standard models, thus, the provided documentation is adequate.
Inputs and Parameters	Other inputs	194	1	Wade	The Design Space Query within the Data Visualization Tool allows the user to set a continuous range of variables within the design space range. Although this capability is useful for parametric studies, the following risks are incurred with some of the variables.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Other inputs	195	1	Wade	The sliders for "Eng. Eff" and "Driveline Eff." would allow the user to arbitrarily change engine efficiency or driveline efficiency uniformly over the map without having a technical basis for such changes.
Inputs and Parameters	Other inputs	196	1	Wade	The slider for weight would allow the user to add hybrid or diesel engines with signficant weight increases without incurring any vehicle weight increase.
Inputs and Parameters	Other inputs	197	1	Wade	Recommendation: A default weight increase/decrease should be added for each technology. If weight reductions are to be studied, then the user should have to input a specific design change, with the appropriate weight reduction built into the model, rather that having an arbitrary slider for weight.
Inputs and Parameters	Section 3.2 Ground Rules for Study	63	1	McBroom	The vehicle and technology selection process needs further discussion. My experience in these large simulation studies is that the vast majority of the time needs to be spent on the selection and once selected agreeing upon the model/data.
Inputs and Parameters	Section 4	64	1	McBroom	There was no model data provided. Engine maps, transmission efficiency maps, battery efficiency maps etc need to be in the Appendices. The black box nature of the inputs is disconcerting.
Inputs and Parameters	Section 4.1.1.1 CPS	65	1	McBroom	How were the profiles selected? Was there an optimization process for each engine size of a given engine type?
Inputs and Parameters	Section 4.1.1.2 DVA	66	1	McBroom	Was the actuation power requirement accounted for? What were the timing/lift profiles and what control strategy was used to select the timing/lift profile? Was this an active model or was the timing/lift profile preset and then unchangeable. I would expect that as the engine size changes and the boost changes the timing/lift profile will have to change with it.
Inputs and Parameters	Section 4.1.3 Boosting Systems	67	1	McBroom	What about superchargers? Eaton's AMS supercharger systems offer high efficiency supercharges that are comparable to turbo's and don't have the lag problem.
Inputs and Parameters	Section 4.1.4 Other Engine Technologies	68	1	McBroom	regarding global engine friction reduction, what value(s) was assigned to that? Was it the same across all engines? If so, why?
Inputs and Parameters	Section 4.2 Engine Configurations	71	1	McBroom	Quantification needed …"The combinations of technologies encompassed in each advanced engine concept provide benefits to the fueling map…."

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Shift Optimizer	386	2	Midlam-Mohler	Shifting strategy impacts efficiency, performance, and drivability. Manufacturers are aware of this and balance all three when calibrating shift maps. Changing baseline shift maps to improve efficiency will have an impact on the other metrics which are also important to the vehicle. Additionally, it is not clear how the optimized shift strategy was developed, what the shift strategy is, or how it will be applied to the range of transmissions in the study. It is stated that is optimizes BSFC, however, there are other constraints that must be applied in addition to this.
Inputs and Parameters	SI Engine Maps and Diesel Engine Maps	394	2	Midlam-Mohler	The baseline engine map data is shown in a series of figures and references are provided for the specific vehicle that the map is for. It is assumed that this indicates that this data has been measured experimentally. If this is the case, then this is well documented.
Inputs and Parameters	SI Engine Maps and Diesel Engine Maps	395	2	Midlam-Mohler	For the 2020 engine maps, there is insufficient detail in this presentation on how the maps were generated. Getting accurate simulation requires careful validation of the model as well as the data in the model – these engine maps are not sufficiently well documented for me to make a judgment on their suitability for the overall goal of the simulator. I am well aware that these future engines do not exist, but there had to be some process of generating these engine maps. Without more information on this process it is simply not possible to comment on their accuracy.
Inputs and Parameters	Transmission technology selection	173	1	Wade	The transmission technologies selected for this study, listed in Table 5.3 (page 23) are appropriate.
Inputs and Parameters	Transmission technology selection	174	1	Wade	The forecast that current 4-6 speed automatic transmissions will have 7-8 speeds by 2020-2025 is appropriate for all except the smallest and/or low cost vehicles (page 19).
Inputs and Parameters	Transmission technology selection	175	1	Wade	The report mentions that the transmissions include dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants (page 22).
Inputs and Parameters	Transmission technology selection	176	1	Wade	Recommendation: The detailed assumptions showing how the benefits of dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants were added to the transmission maps should be added to the report before it is released.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters	Transmissions	360	1	Midlam-Mohler	This peer reviewer is not as well-practiced in transmissions as in other areas in this review. Because of this, a more limited review was conducted of this aspect of the report. As with the other areas of the report, the general concern in this area is the inadequacy of documentation of the modeling approach and validation.
Inputs and Parameters	Turbo Lag	391	2	Midlam-Mohler	The data and methods used in modeling turbo lag are appropriate and there is sufficient explanation and data to support the model.
Inputs and Parameters	Vehicle model issues	303	1	Midlam-Mohler	The vehicle model is described as “a complete, physics-based vehicle and powertrain system model” developed in the MSC.Easy5TM simulation environment. This description is not particularly helpful in defining the type of model as portions of the model are clearly not physics based, such as the various empirical maps used or sub-models like the warm-up model which is by necessity an empirical model due to the complexity of the warm-up process compared to the expected level of fidelity of the model. It is assumed that a standard longitudinal model accounts for rolling losses, aero losses, and grade is used to model the forces acting on the vehicle. Input parameters for the vehicle model are not described. The baseline vehicle platforms are listed, however, the relevant loss coefficients are not provided (rolling resistance, drag coefficient, inertia.)
Inputs and Parameters	Warm-Up Methodology	332	1	Midlam-Mohler	The report describes a 20% factor applied to bag 1 of the FTP-75 for baseline vehicles and a 10% factor applied to the advanced vehicles. The motivation for these factors is described qualitatively and is valid, as many organizations are currently investigating strategies to selectively heat powertrain components to combat friction effects. However, the values for these factors that were selected are not backed up with any data or citation. It is suspicious that the two values cited are such round numbers - the data from which these numbers are derived should be cited. Because of the complexity of this phenomenon, some type of empirical model is justified. The model described in the report is not sufficiently validated to judge its suitability.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters		20	1	Assanis	The report describes a comprehensive set of engine and vehicle technologies for the prediction of GHG emissions and performance. However, the full range of inputs and parameters is not explicitly presented. It requires the reader to refer to the Data Visualization Tool figures to simulation environment, it is impossible to extract details on, or judge the basis for a number of critical inputs. In some occasions, the report mentions that published data have been used, but there are no references to the source. Baseline engine maps, torque converter maps and shifting maps, electric machine efficiency maps, and control strategies for hybrids, which have very direct effects on vehicle performance and emissions, should be presented in the report, at least in a limited format.
Inputs and Parameters		21	1	Assanis	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: Any published fuel economy maps, or other related data, with actual numbers. For proprietary maps and data, a normalized representation would be useful, as well, without the actual bsfc values shown on the map.
Inputs and Parameters		22	1	Assanis	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: Baseline maps used to represent turbomachinery, in actual or normalized form.
Inputs and Parameters		23	1	Assanis	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: The baseline vehicle cooling system and accessory schematic vs. cooling system and accessory load schematics of the future engines considered in the simulation.
Inputs and Parameters		24	1	Assanis	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: Details of EGR modeling parameters, such as maps showing percentage of EGR being used at various loads.
Inputs and Parameters		25	1	Assanis	Some examples of the types of inputs and parameters that would be helpful to include the following in the report: Details of warm-up model parameters, such as ambient temperature; warm up friction correction; cold start fuel consumption correction factor; generation of heat rejection maps for various combinations in the simulation matrix.
Inputs and Parameters		26	1	Assanis	The engine technology selection appears somewhat limited in terms of the selected combinations. For example, why is the Atkinson engine not boosted as well? Moreover, a variable valve actuation technology, as common and important as variable cam phasing, is not included. As already stated in the introductory comments, advanced combustion technologies, such as HCCI, are worth considering. More flexibility in the engine and vehicle parameters would also allow better understanding of the improvements obtained for individual technologies and possibly even show some potential synergies not currently

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
					identified.
Inputs and Parameters		27	1	Assanis	Alternative fuels are currently a key research topic and very important for future energy independence. Because usage of these fuels can have an impact on efficiency and emissions, the study would be enhanced if engine performance maps with various fuels were included.
Inputs and Parameters		69	1	McBroom	How was the FEAD electrification energy balance accomplished? Was additional load placed on the alternator?
Inputs and Parameters		70	1	McBroom	No mention or consideration of cylinder deactivation technologies. This seems like pretty low hanging fruit, even on downsized boosted engines, especially if you deploy DVA.
Inputs and Parameters		72	1	McBroom	How were baseline BFSC maps modified? Was it across the board improvement or were improvements only attributed to certain parts of the map?
Inputs and Parameters		74	1	McBroom	Limiting the alternator to 200A is very conservative, particularly if the system voltage stays at 14V.
Inputs and Parameters		75	1	McBroom	Is there any accounting for the energy conversion on hybrids from the high voltage bus to the low voltage?
Inputs and Parameters		401	2	McBroom	Battery Model: Overall the battery model is sound; however, I don't understand why cold modeling is included. The FTP testing doesn't include cold testing therefore only 25C and up should be included and the battery is consistent at those temps.
Inputs and Parameters		402	2	McBroom	Engine Model: I see data on the HEDGE engine technology but no mention of it in the list of engine technologies unless it's the high EGR DI gasoline engine.
Inputs and Parameters		403	2	McBroom	Engine Model: The trend in engine technology is forced induction (engine downsizing). I think the selection of turbo only is too limiting. I anticipate variable speed supercharging and other combination of forced induction. I think the study would do well to include this.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters		404	2	McBroom	Rgen Alternator: Ricardo (2011) states - 70% efficient alternator; however, alternator efficiency is a function of temp, speed and load. 70% is probably the best, but it's highly unlikely that it will operate there for the duration of the conditions.
Inputs and Parameters		405	2	McBroom	Diesel Engine Fuel Maps: The presentation shows the technologies to be deployed, but doesn't discuss how the 2020 bsfc maps were arrived at. It might be helpful to also use the same method for comparison that the authors used to show LBDI vs EGR.
Inputs and Parameters		406	2	McBroom	Diesel Technology: Curious about the author's comment regarding supercharging, "advances to avoid variable speed". Why not variable speed?
Inputs and Parameters		407	2	McBroom	Curious about why no discussion of advanced materials in engines to achieve improvements.
Inputs and Parameters		408	2	McBroom	EBDI Engine: Couldn't find fuel economy benefit discussion in presentation. Should be done as gasoline or energy equivalent. I know CO2 is proportional, but….
Inputs and Parameters		409	2	McBroom	Future Developments in Engine Friction – I think it would be worthwhile to point out that there are technologies that are more driven by increased durability rather than fuel economy but they could play off one another. Engine friction reduction is one of those areas.
Inputs and Parameters		296	1	Midlam-Mohler	From a high level, it is clear what the inputs to the design space tool are, which are listed in tables 8.1 and 8.2. At the next level down (i.e. the vehicle and subsystem models) there is no comprehensive handling of inputs in parameters in the report. Some models are partially fleshed out in this area but most are lacking. By way of example, the engine models are described as maps which are "defined by their torque curve, fueling map, and other input parameters" where "other input parameters" are never defined.
Inputs and Parameters		302	1	Midlam-Mohler	The simulation methodology is generally not described in the report in sufficient detail to assess the validity and accuracy of the approach. The models and approach are described qualitatively; however, this is insufficient to truly evaluate the ability of the modeling approach to perform the desired function. The following subsections address specific issues with the models, inputs, and parameters and suggest possible corrective actions to address these issues.
Inputs and Parameters		1	1	Sawyer	The vehicle classes and baseline exemplars are reasonably chosen, within the constraint that vehicle size, footprint, and interior volume for each class be locked to the 2010 base year. It is likely that new vehicle classes will emerge by 2025 and/or that these "locking" restraints will be relaxed.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters		2	1	Sawyer	The design of experiment (DoE) ranges, Tables 5.4, 5.5, 8.1, and 8.2, are reasonable and do not exclude likely sizings. The assumed alternator baseline and advanced alternator efficiencies are reasonable. The assumed reduction in automatic transmission losses is reasonable, but not aggressive for 15 development years from the baseline year. Similarly the state-of-charge swing for hybrid modeling of 30-70% is reasonable, but does not reflect improved battery technology for the 2020-25 period, which should allow a greater swing for reduced battery size, weight, and cost.
Inputs and Parameters		419	2	Sawyer	Ricardo, Action Item Response, 16 Feb 10, 15 p. (proprietary): A response to an EPA inquiry, this document deals with engine maps, engine map comparisons, engine map plots, transmissions, batteries, motor and generator efficiency maps. Comment: Ricardo (2011) responses and data selection seem reasonable.
Inputs and Parameters		420	2	Sawyer	Ricardo, Baseline Camry with Alternator Regen and Shift Optimizer Development of Optimized Shifting Strategy Light Duty Vehicle Complex Systems Simulation EPA Contract No. EP-W-07-064, work assignment 2-2, 15 Apr 10, 10 p. (proprietary): This document provides data on effectiveness of shift optimizer, including alternator regen, over the FTP and HWFET. Comment: Seems reasonable, improvements are greater on FTP than HWFET.
Inputs and Parameters		421	2	Sawyer	Carlson, R., et al., Argonne National Laboratory, On-Road Evaluation of Advanced Hybrid Electric Vehicles over a Wide Range of Ambient Temperatures EVS23 – Paper #275, 15 p. Paper reports on-road and dynamometer testing of two hybrid vehicles at cold (-14 degC) and hot (33 decC) conditions. Fuel economy increases with temperature (except for highest temperatures with the system which does not limit battery temperature).Comment: Paper provides data showing importance of temperature on hybrid vehicle fuel economy. These data are used by Ricardo to validate their battery warm up model, see next document.
Inputs and Parameters		424	2	Sawyer	Mischker, K. and Denger, D., Requirements of a Fully Variable Valvetrain and implementation using the Electro-Hydraulic Valve Control System EHVS, 24th International Vienna Engine Symposium 2003, 17 p. This paper describes an electro-hydraulic valve system (EVHS) and limited data on reduction in bsfc. Comment: This would seem to be of limited quantitative value since technology is well advanced beyond 2003.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters		425	2	Sawyer	Ricardo, Engine and Battery Warm-Up Methodology, Light Duty Vehicle Complex Systems Simularion, 17 Feb 10, 16 p. (proprietary) Document reviews engine and battery warm-up strategies and provides a simple model. Comment: The approach to battery warm-up is uncertain. Points to importance of test cycle (FTP for fuel economy compliance versus test for EPA label versus real-world).
Inputs and Parameters		428	2	Sawyer	Ricardo, EBDI Project Overview, Ethanol Boosted Direct Injection, Nov 09, 8 p. This study examines ethanol boosted direct injection (EBDI) to optimize engine operation of E85 fuel. Possibility exists to match or exceed diesel performance and reduce CO2 emissions. Comment: It is not clear if comparison of EBDI and diesel is a equal technology level.
Inputs and Parameters		430	2	Sawyer	UOM, HiTor® for elecgtric, hybrid electric, and fuel cell powered vehicles, 18 Aug 09, based on test data map, 5 p. Describes power electronics for motor generator control, including an efficiency map for combined controller and motor based on test data. Comment: Efficiency maps seem reasonable.
Inputs and Parameters		432	2	Sawyer	UOM, PowerPhase®75 for electric, hybrid electric, and fuel cell powered vehicles, not dated, 6 p. Described power electronics of vehicle electric power. Comment: Similar to earlier brochure on power electronics, including efficiency map.
Inputs and Parameters		437	2	Sawyer	Ricardo, Hybrids Control Strategy, 6 Aug 10, 41 p. (proprietary) Discusses development of control strategies for P2 and Power Split hybrids. Comment: includes efficiency maps and substantial technical detail including vehicle mass effect.
Inputs and Parameters		439	2	Sawyer	Ricardo, Assessment of Technology Options, 18 Nov 09, 14 p. (proprietary) Assessment of hybrid technologies using evaluation template. Comment: Treats a range of hybrid technologies, including series hydraulic, giving projections of CO2 reduction benefits.
Inputs and Parameters		440	2	Sawyer	Ricardo, Simulation Input Data Review, 2 Feb 10, 30 p. (proprietary) Document review modeling parameters for vehicle performance simulations, including engine efficiency maps for a range of engine and transmission technologies. Comment: This is the kind of data that we requested. Includes shift strategies. Seems reasonable and well-documented.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Inputs and Parameters		449	2	Sawyer	Ricardo, Conventional Automatic Nominal Results, 16 Mar 10, 17 p. (proprietary) This presentation includes mileage versus 0-60 mph time maps for a range of vehicles (light duty to large truck). Also presented are comparisons of fuel economy for different regulatory test cycles and technologies.Comment: Significance not clear.
Inputs and Parameters		451	2	Sawyer	Ricardo, Revised follow-up answers for hybrid action items, 23 Jun 10, 16 p. (proprietary) This report answers questions on electric drive train efficiency, battery characteristics, and available braking energy, and more. Comment: Interesting data, but implication not clear.
Inputs and Parameters		459	2	Sawyer	Ricardo, Assessment of Technology Options, Technologies related to Transmission and Driveline, 19 Nov 09, 21 p. This document described transmission technologies, including timing of their introduction. Comment: Seems reasonable.
Inputs and Parameters		462	2	Sawyer	Ricardo, Assessment of Technology Options, Technologies related to Vehicle-level Systems, 24 Nov 09, 16 p. This review of vehicle technologies that can improve vehicle efficiencies provides a basic description and information on expected levels of CO2 reduction. Comment: This is a clear description of anticipated improvements in vehicle technologies that reduce load and fuel consumption.
Simulation methodology	Major deficiencies in the report	199	1	Wade	An overall schematic and description of the powertrain and vehicle models and the associated subsystem models/maps were not provided. Only vague descriptions were included in the text of the report.
Simulation methodology	Major deficiencies in the report	200	1	Wade	Technical descriptions of how the subsystems and vehicle models/maps for the baseline vehicles were developed were not provided.
Simulation methodology	Major deficiencies in the report	201	1	Wade	Most importantly, only non-technical descriptions of how each of the advanced technology subsystem models/maps was developed were provided.
Simulation methodology	Major deficiencies in the report	202	1	Wade	Descriptions of the algorithms used for engine control, transmission control, hybrid system control, and accessory control were not provided.
Simulation methodology	Major deficiencies in the report	203	1	Wade	Descriptions of how synergistic effects were handled were not provided.
Simulation methodology	4.4 Transmission Technologies	88	1	McBroom	How were the gear ratios selected? What about shift logic?

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Simulation methodology	6.3 Engine Models	92	1	McBroom	two methods to develop engine models were discussed. It is not disclosed which approach was used for which engine. I recommend that one approach be developed for all engines or both approaches be applied to each engine to converge to a solution.
Simulation methodology	6.3.1 Warm-up Methodology	95	1	McBroom	How was the engine warmup modeled? Is it a first order transfer function with a time constant? It said proprietary data was used, but how? Does the method allow for different warmup depending on size and engine technology?
Simulation methodology	6.3.2 Accessories	96	1	McBroom	Constant alternator efficiency and load is not a very good assumption. New alternator technologies and higher alternator loads due to electrification and increased electrical demands. Will the future still continue to use 14V or will higher voltages be used?
Simulation methodology	6.8 Hybrids	97	1	McBroom	Were separate optimization runs to determine the best control strategy done? How are we assured the best control strategy is implemented?
Simulation methodology	7.2 Nominal Runs	98	1	McBroom	Was a separate matrix of simulations run to obtain the nominal sizes for the advanced engine or was it merely a matter of matching the peak torque.
Simulation methodology	Accessories Models (Section 6.3.2)	38	1	Assanis	Specific suggestions regarding models that need more detailed coverage: Alternator efficiency has been assumed to be constant around 55% for baseline. In the current baseline vehicles the alternator efficiencies do vary with the temperature and load.
Simulation methodology	Accessories Models (Section 6.3.2)	39	1	Assanis	Specific suggestions regarding models that need more detailed coverage: Has AC compressor load been considered in any of the simulations? In some of the new cycles being proposed by EPA, it is required that AC remains ON throughout the cycle. Hence, management of the AC load is very critical.
Simulation methodology	Baseline vehicle model validation results	204	1	Wade	Ricardo (2011) developed baseline vehicle simulations for 2010 vehicles for which EPA fuel economy data were available (page 30). "For the 2010 baseline vehicles, the engine fueling maps and related parameters were developed for each specific baseline exemplar vehicle." (page 25). Even though these are production vehicles, the models and maps used were not described (including whether they were derived from actual measurements or models) and they were not provided in the report so that their appropriateness could not be assessed.
Simulation methodology	Baseline vehicle model validation results	205	1	Wade	Table 7.1 shows the calculated vs. EPA test data for the baseline vehicle fuel economy performance. This table should include percentage variation of the model calculations vs. the test data. The agreement of the model with the test data is within 11%, but this is a larger error than some of the incremental changes shown in Appendix 3. A closer agreement would have been expected.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Simulation methodology	Baseline vehicle model validation results	206	1	Wade	Recommendation: A closer examination of the reasons for the up to 11% discrepancies between the models and baseline vehicles' EPA fuel economy test data should be undertaken so that the models could be refined to provide better agreement.
Simulation methodology	Cold Start Correction Methodology	384	2	Midlam-Mohler	The correction used to adjust fuel economy for cold start is described in this presentation. The method is based on two pieces of information:1. A set of three tests from a single vehicle's instantaneous fuel multiplication correction factor2. A piece of EPA data which shows a fleet-wide average for 2007 of the instantaneous fuel multiplication correction factorThe instantaneous fuel multiplication correction factor is not described in the presentation, however, it is assumed to be the sum of the "short term fuel trim" and "long term fuel trim." If this is the case, then this value doesn't correlate to increased fuel consumption, but rather, to errors in the injector characterizations, fuel property assumptions, and air estimation algorithm in the engine controller. The engine controller is going to maintain stoichiometry based on oxygen sensor measurements, these trim values are the simply the feedback correction values required to do this based on the feedforward algorithm in the ECU. By way of example, I could alter the fuel tables of an ECU by 15% which would cause the feedback control system to correct by an opposite 15%. This would not change the fuel consumption of the vehicle once the control system has corrected it, which would happen in seconds.I don't disagree necessarily with the magnitude of the outcomes, since they are based mostly on EPA bag fuel economy data. If I am correct in my understanding of the correction factor then the method is not valid.
Simulation methodology	Constraints	41	1	Assanis	Specific suggestions regarding models that need more detailed coverage: There is no discussion in the report that discusses the constraints on the combinations that can be implemented in real life. For example, would a multi-air system that is currently designed for small size engines work for a full size car?

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Simulation methodology	Engines and Engine Models (Sections 4.1 and 6.3)	30	1	Assanis	Specific suggestions regarding models that need more detailed coverage: It is not clear whether the engine maps in the simulation tool were generated based on simulations or existing experimental data, somehow fitted and scaled to the various configurations. In general, the explanation on how maps were obtained is vague for such an important component. In one section, the report states that the fueling maps and other engine model parameters used in the study were based on published data. If so, it would be nice to have a list of the published materials that have been used as the resource. In Section 4.2, the report states that the performance of the engines in 2020-25 were developed by taking the current research engines and assuming the performance of the 2020 production engines will match that of the research engine under consideration. Does this assumption take into account the emission standards in 2020, and do the current research engines match those emission standards? What is the systematic methodology that has been adopted to scale the performance and fuel economy of current baseline engines to engine models for 2020-25? Also, the report lacks detail concerning the methodology of extrapolating from available maps to maps reflecting the effects on overall engine performance of the combination of the future technologies considered.
Simulation methodology	Engines and Engine Models (Sections 4.1 and 6.3)	31	1	Assanis	Specific suggestions regarding models that need more detailed coverage: The report lacks detail on the specifics on the different engine design and operating choices. For instance, what was the compression ratio (and limit) that was used? What is the equivalence ratio, or range considered, for the lean burn engine? How much EGR has been used across the speed and load range? What constraints, if any, were applied to the simulations to account for combustions limitations such as knock and flammability limits? The NOx aftertreatment/constraints section could also be expanded.
Simulation methodology	Engines and Engine Models (Sections 4.1 and 6.3)	32	1	Assanis	Specific suggestions regarding models that need more detailed coverage: In cases where engine models have been used to generated maps, how was combustion modeled? For instance, discussion is made as to the heat transfer effect resulting from surface to volume changes connected to downsizing. More detail on the heat transfer assumptions that go into the applied heat transfer factor would be helpful. Was heat transfer modeled based on Woschni's correlation? What about friction scaling with piston speed? This would change with stroke at a constant RPM. Also friction would change with the number of bearings and cylinders.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Simulation methodology	Intelligent Cooling Systems (Section 4.3.1)	34	1	Assanis	Specific suggestions regarding models that need more detailed coverage: The report describes intelligent cooling systems, but does not provide any estimates of the anticipated reductions in fuel consumption over the FTP cycle, though related papers have been published in the open literature.
Simulation methodology	Intelligent Cooling Systems (Section 4.3.1)	35	1	Assanis	Specific suggestions regarding models that need more detailed coverage: Sizing of various cooling components plays a very crucial role in fuel economy predictions. The report does not provide any detail on how the optimum cooling flow required for a given engine-transmission combination was determined. This would significantly affect the oil, coolant and transmission oil pump RPMs, which would in turn significantly change the accessory loads.
Simulation methodology	Intelligent Cooling Systems (Section 4.3.1)	36	1	Assanis	Specific suggestions regarding models that need more detailed coverage: In addition, the report does not have any discussion on how modified cooling components (radiator, condenser, etc.) would be sized for more efficient powertrains. For instance, a more efficient engine that would reject less heat would likely need a smaller radiator and lesser airflow through the radiator; hence, the grill opening could be reduced to cut down on aero drag. A high efficiency transmission will not reject a lot of heat to the transmission oil; thus, a smaller transmission oil cooler could be used.
Simulation methodology	Scaling Methodology Review	393	2	Midlam-Mohler	With one exception, the scaling methodology appears to be sound given the information provided in the presentation. The curve used to adjust BSFC with displacement ratio is not supported with data or any citation of where it originated. The motivation for this correction seems valid, however, it needs to be supported with data.
Simulation methodology	Section 3.4 CSM Approach	77	1	McBroom	Is the CSM approach used in other applications? If so it would be helpful to give citations. If it was developed by Ricardo, that should be stated. The discussion refers to physics based models, but other than that very little about the type of modeling is discussed. I recall on the phone call that lumped parameter models were mentioned. There is no discussion of that.
Simulation methodology	Section 4.1.1 Advanced Valvetrains	82	1	McBroom	There is no explanation of how CPS and DVA systems were modeled. There was only a description of what CPS and DVA is.
Simulation methodology	Section 4.2.1 Stoich DI Turbo	83	1	McBroom	Quantify how did the cooled exhaust manifold/lower turbine inlet temp improved the BSFC map. This is a good example of technology interaction…how did the radiator size grow to accommodate the additional heat rejection; how did the frontal area of the vehicle change to accommodate the larger radiator?

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Simulation methodology	Section 4.2.2 Lean Stoich Switching	84	1	McBroom	This type of tech points to one of the dangers of optimizing configuration/technology/control strategy to the drive cycles; that is that it has the potential to over constrain the design and effect the "real world" performance/fuel economy.
Simulation methodology	Section 4.2.4 Atkinson Cycle	85	1	McBroom	How do the 2020-2025 maps differ from the 2010 maps?
Simulation methodology	Section 4.2.5 Advanced Diesel	86	1	McBroom	Why were only the benefits of improved pumping losses or friction considered? What improvements were assigned to these benefits? Was it across the board or regional? What about advanced boosting technology for these engines?
Simulation methodology	Section 6 Vehicle Models	89	1	McBroom	No discussion of how driveline inertia is handled. This is important in forward-looking models.
Simulation methodology	Transmission Models (Section 6.4)	40	1	Assanis	Specific suggestions regarding models that need more detailed coverage: The transmission efficiencies vary by almost 10-15% based on the transmission oil temperature. How have these effects been modeled?
Simulation methodology	Transmission optimization	207	1	Wade	A transmission shift optimization strategy is presented in the report and the results are shown in Figure 6.1 (page 28). This figure shows very frequent shifting, especially for 4th, 5th and 6th gears.
Simulation methodology	Transmission optimization	208	1	Wade	Issue: Optimized shift strategies of the type used by Ricardo (2011) have been previously evaluated and found to provide customer complaints of "shift busyness". Customers are likely to reject such a shift strategy.
Simulation methodology	Turbocharger systems (Section 4.1.3)	33	1	Assanis	Specific suggestions regarding models that need more detailed coverage: There is no discussion of turbocharger efficiencies and their range. Did the simulations assume current boosting technologies? Were maps used for this simulation or some other representation? Was scaling used? What were the allowed boost levels?
Simulation methodology	Vehicle model issues	209	1	Wade	Although the report described the major powertrain subsystems included in the vehicle models (page 24), a description of the vehicle model was not provided.
Simulation methodology	Vehicle model issues	210	1	Wade	Issue: A description of how aerodynamic losses, tire rolling losses and weight are handled in the model was not provided.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Simulation methodology	Warm-up methodology (Section 6.3.1)	37	1	Assanis	Specific suggestions regarding models that need more detailed coverage: This section talks about using engine warm-up profile during the cold start portion to ascertain additional fueling requirements. It talks about a correction factor to account for this additional fuel. How was this factor determined? Has a different correction factor been used for various engines? For instance, for a lean-burn engine that reject less heat, the oil warm-up is slower compared to a baseline engine. Was a new heat rejection map generated to account for start-up enrichment while modeling the warm-up? What is the ambient temperature that has been considered while performing the FTP 75 fuel economy test? Have the viscous effects of engine oil considered in the warm up simulation? How have the friction losses for various valvetrain engine combinations been modeled?
Simulation methodology		28	1	Assanis	The RSM approach is certainly a good way to provide quick access to wide range of results, but it has the limitation that a large number of assumptions have to be made ahead of time in order to determine the design space. Also, creating these encompassing RSM's requires a significant amount of simulations, and all the results will not necessarily be of interest. If a more flexible model/simulation was created and coupled to a user-friendly interface, users might be able to obtain and analyze the desired results instead of being constrained by the design space previously determined.
Simulation methodology		29	1	Assanis	Even though the authors attempt to describe the simulation methodology and assumptions in the report, it lacks details of the models employed, which makes it hard to determine if refinements need to be made, or even if more appropriate models/methods should be used. It is understandable that, due to the proprietary data, it is not possible to present everything.However, without any of this information, the RSM results are more difficult to interpret.
Simulation methodology		78	1	McBroom	Some assessment of the model uncertainty would be helpful. This could be a qualitative rating assigned by the advisory committee or a more rigorous method could be used.
Simulation methodology		79	1	McBroom	More detail on the types of models is required. Do some models use first principals of physics and others lumped parameter?
Simulation methodology		80	1	McBroom	ANOVA or some other analytical approach to consider technology interactions needs to be deployed.
Simulation methodology		81	1	McBroom	It says a statistical analysis was used to correlate variations in the input factors to variations in the output factors. This is ambiguous. What analysis method was used? Where is it reported? I didn't see anything in the results about this. It was used to generate the RSM, but what was the measure of fitment? How did the RSM fit compare from vehicle config to

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
					vehicle config.
Simulation methodology		87	1	McBroom	Ricardo's expectation for pace and direction: I thought there was an advisory committee making these decisions. I'm surprised that they think boost will be limited to 17-23bar.
Simulation methodology		90	1	McBroom	There are several types of rolling resistance models, what type was used?
Simulation methodology		91	1	McBroom	Was coast-down data from the baseline vehicles obtained or where the coefficients of rolling resistance and Cd modified to get the data to match?
Simulation methodology		93	1	McBroom	Regarding engine downsizing, I'm not sure that the scaling approach applies to boosted engines, especially engine with multiple compressors as well as DVT and CPS technology.
Simulation methodology		94	1	McBroom	Turbo lag applied as a first order transfer function with a time constant. How was the time constant selected? Was it validated? How was the improvement attributed to turbo compounding modeled?
Simulation methodology		99	1	McBroom	How was a 20% reduction in engine size for the nominal hybrid engine arrived at? Even for the micro-hybrid (engine start/stop)?
Simulation methodology		100	1	McBroom	"These summary results….used to assess the quality of the simulation…." Where is the data for this assessment published? What were the criteria that said pass or fail?
Simulation methodology		410	2	McBroom	Transmission Model: Ricardo (2011) describes an approach that asserts that using an average efficiency value vs a 3D efficiency map yields insignificant differences over the CAFÉ drive cycles, but offers no results to validate the claim.
Simulation methodology		411	2	McBroom	Transmission Model: Ricardo (2011) offers no discussion of how inertial changes are managed during shifts. This may have greatest impact on the shift strategies where the transmission shifts to put the engine at the best bsfc for the given load.
Simulation methodology		412	2	McBroom	Hybrid: I don't see any effort to model motor/inverter temperature effects. One would expect significant degradation of motor capability as things heat up during normal operation.
Simulation methodology		413	2	McBroom	Regen Alternator: Alternator model is too simplistic. On average the efficiency is too high as identified and it's unrealistic to assume that the battery will be able to accept 100% of the charge.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Simulation methodology		414	2	McBroom	EHVA: The paper addresses the potential of the technology nicely. Since it was published in 2003 has any more recent work been done to address the durability and issues brought up in the conclusions?
Simulation methodology		415	2	McBroom	Accessories: I don't see any discussion on the treatment of accessories. I believe from my review of the previous material, that the authors assume that all accessories will be electric. I think that engine driven accessories will play a key role in 2020.
Simulation methodology		297	1	Midlam-Mohler	The vehicle model is reported as "a complete, physics-based vehicle and powertrain system model" - which it is not. The modeling approach used relies heavily on maps and empirically determined data which is decidedly not physics-based. This nomenclature issue aside, the model is not described in sufficient detail in the report to make an assessment in this area. An excellent example of this is the electric traction drives and HEV energy storage system for which the report mentions no details, even qualitative ones, on the structure of the models.
Simulation methodology		369	1	Midlam-Mohler	The vehicle simulator is used to generate several thousand simulations using a DOE technique. This data is then fit with a neural-network-based response surface model in which the "goal was to achieve low residuals while not over-fitting the data." This response surface model then becomes the method from which vehicle design performance is estimated in the data analysis tool. In this case, the response surface model is nothing more than a multi-dimensional black-box curve fit. There was no error analysis given in the report regarding this crucial step. By way of example, the vehicle simulator could provide near perfect predictions of future vehicle performance; however, a bad response surface fit could corrupt all of the results.
Simulation methodology		370	1	Midlam-Mohler	Provide error metrics for the neural network RSMs (i.e. R2, min absolute error, max absolute error, error histograms, error standard deviation, etc.) before combining the fit and validation data sets.
Simulation methodology		371	1	Midlam-Mohler	Provide the error metrics described above for the RSMs after combining the fit and validation data sets.
Simulation methodology		372	1	Midlam-Mohler	Provide validation that the data analysis tool correctly uses the RSM to predict results very close to the source data (i.e. demonstrate the GUI software behaves as expected).

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Simulation methodology		3	1	Sawyer	Ricardo (2011) simulated dynamic vehicle physical behavior using MSC Easy5TM software with 10 Hz time resolution. This software and the time resolution are appropriate for the computations to show the effect of component interactions on vehicle performance. 10 Hz time resolution is sufficient to capture both driver behavior and vehicle response. Should the application of information technology, as is being implemented, as a means of vehicle control for reducing fuel consumption become a future strategy, the model should be able to provide a suitable simulation.
Simulation methodology		4	1	Sawyer	Drivetrain synergistic effects seem to be predicted reasonably. This was demonstrated by calculation of fuel economy of the baseline vehicles and comparison with EPA certification test data. The model does not seem to have the capability to capture vehicle weight-drivetrain synergistic effects. Vehicle weight reductions associated with drivetrain efficiency improvements are input rather than modeled internally. This is an important deficiency. Similarly, from the Complex System Tool, weight reductions do not seem to result in reduction in engine displacement.
Simulation methodology		422	2	Sawyer	Ricardo, Hybrid Battery Warm Up Model Validation – Update, Light Duty Vehicle Complex Systems Simulation ,EPA Contract No. EP-W-07-064, work assignment 2-2, 15 Mar 10, 5 p. proprietary) This report presents a simple battery heat transfer model for battery warm up and compares with Argonne National Laboratory of the previous document.Comment: Model produces adequate prediction of battery temperature.
Simulation methodology		441	2	Sawyer	Trapp, C., et al., Lean boost and NOx—strategies to control nitrogen oxide emissions, (no date), 23 p. Technical paper that describes lean burn direct injection (LBDI) engines, SCR NOx control, and more. Includes some emission control cost data. Comment: Not clear how this related to Ricardo's model development for EPA.
Simulation methodology		453	2	Sawyer	Ricardo, Scaling Methodology Review, 19 Jan 10, 9 p. This document explains the scaling methodology used in the EASY5 vehicle model. Comment: This description in clear and useful.
Simulation methodology		458	2	Sawyer	Takoaka, T., et al., Toyota, Super high efficient gasoline engine for Toyota hybrid system, (no date), 16 p. This paper describes the hybrid system, IC engine interaction that allows increased IC engine efficiency. Comment: Of general interest but application to the model not clear.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Simulation methodology		198	1	Wade	Concern: Methodologies used in simulating the subsystems and the overall vehicles were not provided, so that the validity and applicability of these methodologies cannot be assessed.
Results	5.2 Vehicle Configuration and technology combinations	105	1	McBroom	Also there is no scientific or objective reason given for the DoE ranges. It appears that I can make any vehicle 60% less mass, 70% less rolling resistance etc.…This will skew the results towards that end of the DoE, when they may not be practically achievable.
Results	6.1 Baseline Conventional Vehicle Model	106	1	McBroom	Results were compared to the EPA Vehicle Certification Database. These results often include correction factors and allowances that aren't documented on the sticker. Recommend that actual testing be run to perform the benchmark.
Results	6.3.1 Engine Warmup Methodology	107	1	McBroom	Were there hot and cold engine maps? No mention.
Results	6.4 Transmission Models	108	1	McBroom	Fig 6.1 appears to be a comparison of desired cvt ratio vs desired 6spd gear ratio. Should be stated as such. The shift logic controller should take into account the time to shift and whether or not the desired shift is achievable.
Results	6.5 torque Converter models	112	1	McBroom	The lockup strategy seems very conservative. Large gains are achievable with more sophisticated control and are in use today.
Results	6.6 Final Drive Model	114	1	McBroom	Only discussed the baseline, what improvements for 2020 and what final drive selection criteria for the future vehicles was used?
Results	6.7 Driver Model	115	1	McBroom	How was the soak modeled? Were there hot engine maps and cold engine maps?
Results	7.1 Baseline Conventional Vehicle Models	116	1	McBroom	Better definition of what "acceptably close" means. This doesn't meet the criteria for objectivity. Something like, "the advisory committee determined that the baseline models had to predict within x% to be usable for this study."
Results	8.1 Evaluation of Design Space	118	1	McBroom	Why was Latin hypercube sampling methodology picked over other sampling methods? While it's attributes are mentioned, what other methods were considered?

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Results	8.2 RSM	119	1	McBroom	A description of how the neural network is deployed is needed, only the why it was used is discussed in this section. What were the best fit criteria? What types of equations did the neural net have to play with? Where are the fit's published? How was it determined that the "one fit per transmission" was the best way to go?
Results	9.1 Basic Results	120	1	McBroom	Why 10Hz sampling rate? By what criteria was a run considered good vs bad?
Results	9.3 Exploration of the Design Space	121	1	McBroom	If boundaries of acceptable performance were applied, a considerable number of simulation runs could be eliminated.
Results	Issue with CSM	218	1	Wade	Issue: The technology "package definitions" (page 22 and 23) precluded an examination of the individual effects of a variety of technologies.
Results	Issue with CSM	219	1	Wade	Some examples where the model did not allow a build up of comparison cases are: - Baseline engine with AT-2010 to AT-2020 to DCT - Baseline engine without stop-start to with/stop-start
Results	Other issues	220	1	Wade	The Advanced Diesel does not appear to be modeled for the Standard Car and Small MPV (page 46 and 47), yet no reason was provided.
Results	Other issues	221	1	Wade	The P2 and PS hybrid system was not modeled for the LHDT (page 47), yet no reason was provided.
Results	Other issues	222	1	Wade	When the baseline cases were run in the Complex Systems Model, incorrect values of displacement and architecture were shown in the output. o As an example shown on the attached chart (copied from the output of the CSM), the baseline for the Standard Car with a 2.4L engine shows a displacement of 1.04L. o For the same example, the architecture is shown as "conventional SS", whereas the baseline was understood to not have the stop-start feature (page 22, Table 5-2).
Results	Overview of results	211	1	Wade	The results from this work could be useful in evaluating possible GHG emission reductions in the 2020-2025 timeframe if the issues throughout this peer review were addressed and the recommendations in Item 5 (below) were implemented. However, even if the foregoing deficiencies were resolved, the foregoing caveat that there are numerous technologies that have potential for reduced GHG emissions that were not included in this study must be recognized (see Item 1B, above).

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Results	Sample runs of CSM	212	1	Wade	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Baseline engine with AT6-2010 to Stoichiometric DI Turbo, Stop-Start, AT8-2020-38.7% improvement in M-H mpg- Lumsden, et al. (2009) identified a 25-30% improvement in mpg for a 50% downsized, DI, Turbo engine. The remaining 9-14% potentially could be explained by stop-start and the change from AT6-2010 to AT8-2020 (although the details of the systems and the models used would be needed to make this assessment).
Results	Sample runs of CSM	213	1	Wade	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: AT8-2020 to DCT -3.3% improvement in M-H mpg - This improvement appears reasonable.
Results	Sample runs of CSM	214	1	Wade	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Stoichiometric DI Turbo with Stop-Start to P2 Hybrid - 18.2% improvement in M-H mpg - This improvement appears reasonable.
Results	Sample runs of CSM	215	1	Wade	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Stoichiometric DI Turbo with Stop-Start to PS Hybrid - 11.1% improvement in M-H mpg - A detailed explanation of the differences in the improvements between the P2 and PS hybrids should be provided in the report, especially considering that the P2 hybrid has better fuel economy and uses a 70% smaller electric motor (24 vs. 80 kW).
Results	Sample runs of CSM	216	1	Wade	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Stoichiometric DI Turbo PS Hybrid to Naturally Aspirated Atkinson CPS Hybrid - Loss of 2.3% M-H mpg (From Stoichiometric DI Turbo PS Hybrid) - The details of the Naturally Aspirated Atkinson CPS Hybrid should be provided to explain

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
					the nearly equal fuel economy to the Stoichiometric DI Turbo PS Hybrid.
Results	Sample runs of CSM	217	1	Wade	In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below: Stoichiometric DI Turbo PS Hybrid to Naturally Aspirated Atkinson DVA Hybrid - 2.1% M-H mpg improvement in M-H mpg (From Stoichiometric DI Turbo PS Hybrid) - The details of the Naturally Aspirated Atkinson DVA Hybrid should be provided to explain the nearly equal fuel economy to the Stoichiometric DI Turbo PS Hybrid
Results	Section 4.4.11 Lubrication	103	1	McBroom	Assumes a sweeping improvement without identifying a clear rationale…doesn't appear to describe a scientific or objective approach.
Results	Section 4.4.6 Shifting Clutch Technology	101	1	McBroom	"The technology will be best suited to smaller vehicle segments because of reduced drivability expectations" – not in the US market.
Results	Section 4.4.7 Improved Kinematic Design	102	1	McBroom	Assumes a sweeping improvement without identifying a clear rationale…doesn't appear to describe a scientific or objective approach.
Results	Section 4.5.1 Intelligent Cooling System	104	1	McBroom	The system as described seems more appropriate for regulated emissions reduction opportunity rather than fuel economy or GHG. I think these systems enable engine control strategies that aren't part of this study that would have a greater impact on fuel economy than warming up the engine faster.
Results		42	1	Assanis	For the vehicle performance simulation results shown in Table 7.1, were there any significant adjustable parameters used to fit these vehicles?
Results		43	1	Assanis	Even though it appears that the validation results from the simulation have "acceptably" close agreement with the test data, there are up to 15% off. Even for the small car where all data is available, the error is on the order of 5%. These discrepancies are usually not negligible and should be taken into account when conclusions are drawn from the results, especially if regulation is to be proposed based on these.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Results		44	1	Assanis	There is also no baseline hybrid configuration and no validation of the hybrid model. Due to the increased complexity of these vehicle systems, it is important to ensure the parameters and assumptions are valid.
Results		45	1	Assanis	It would be desirable to include a complete test case with the appropriate inputs, analysis and outputs as part of the report. The sample results presented in figures seem to have been included to indicate the RSM and Data Visualization Tool's capabilities, but they do not provide a complete picture from which to draw solid conclusions.
Results		46	1	Assanis	The plots showing simulation results in blue, red, etc. could be better labeled (i.e. legends could be inserted in the plots) and possibly presented in a relative format indicating percent improvements over the baseline engine rather than absolute numbers. This is more of a personal choice for a more clear representation of the predicted improvement, rather than stating that there is anything wrong with the current representation.
Results		109	1	McBroom	What are the shift optimizer inputs? What are it's basic decision criteria?
Results		110	1	McBroom	There is no discussion of engine downspeeding.
Results		111	1	McBroom	There is no discussion of gear ratio selection.
Results		113	1	McBroom	What was the basis for the minimum rpm's for lockup sited? Should be based on lugging the engine. The controller should recognize when it needs to unlock the TC based on the engines ability to keep up.
Results		117	1	McBroom	On the performance runs, a few tenths of a second represent measurable difference in engine torque for example.
Results		416	2	McBroom	Motor Efficiency Maps: I am having trouble believing that motor efficiency will stay above 90% once temperature effects are accounted for. It also seems to me that these numbers don't include the inverter even though the authors say that it does. The UQM maps seem more reasonable. As stated in a previous comment, I believe that the cost reductions needed for motors will drop their efficiencies in the future.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Results		417	2	McBroom	After reading the papers and presentations I come to the assumption that the papers were used to guide the selection of technology, but it's not clear which maps were generated from model and which maps were generated in the test cell. It's evident that there is a heavy concentration on engine technology and the fidelity of the engine models, which is appropriate. I have a slight concern about the impression I'm left with; that there is not much attention to the interaction of systems effects. This is most likely because of cost and availability of data. I would like to see the EPA articulate a process for looking at system interactions, continuous improvement and model compatibility. For example if the study were to run over several years the researches should feel confident comparing a result generated with the models in 2013 to modeling results generated today.
Results		298	1	Midlam-Mohler	The third charge questions deals with the validity and the applicability of the resulting prediction. The difficulty in this task is that it is an extrapolation from present technology that uses an extrapolation method (i.e. the model) and a set of inputs to the model (i.e. future powertrain data.) Since it is not possible to validate the results against vehicles and technology that do not exist, one can only ensure that the model and the model inputs are appropriate for the task. Because of the lack of transparency in the model and inputs it is difficult to make any claims regarding the results. In trying to validate results, one example is cited in the body of the report that shows the baseline engine getting superior HWFET and US06 fuel economy than all of the other non-HEV powertrains with other factors being the same – this leaves some skepticism regarding the results.
Results		373	1	Midlam-Mohler	As outlined in the executive summary, it was not possible to answer the charge questions provided for this peer review due to lack of completeness in the report. Thus, this report was aimed at providing feedback on what information would be helpful to allow a reviewer to truly evaluate the spirit of the charge questions. With the above in mind, the following conclusions are made.
Results		374	1	Midlam-Mohler	The modeling approach describe in the report could be appropriate for the simulation task required and is generally consistent with approaches used by other groups in this field. The conclusions from the report could very well be sound; however, there is insufficient information and validation provided in the report to determine if this is the case. The technique used to analyze the mass simulation runs could also be sound, although the accuracy of the response surface model is not cited in the report.
Results		375	1	Midlam-Mohler	The process of arriving at the performance of the future technologies is not well described.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Results		376	1	Midlam-Mohler	The majority of models are only described qualitatively making it hard or impossible to judge the soundness of the model.
Results		377	1	Midlam-Mohler	Some of the qualitative descriptions of the models indicate that models do not consider some important factors.
Results		378	1	Midlam-Mohler	Because of the qualitative nature of the model descriptions, there is a major lack of transparency in the inputs and parameters in the models.
Results		379	1	Midlam-Mohler	Where precise value(s) are given for parameters in the model, the report generally does not cite the source of the value(s) or provide validation of the particular value.
Results		380	1	Midlam-Mohler	Validation of the model and sub-models is not satisfactory (It is acknowledged that many of these technologies do not exist, but the parameters and structure of the model have to be based on something.)
Results		5	1	Sawyer	Performance calculations tied to the FTP, HWFET, and US06 test cycles do not adequately capture vehicle behavior under real-world operation. Therefore, technologies that address improving fuel economy under real-world operation are either excluded or their contribution not included. The application of a 20% reduction in fuel economy to the FTP75 bag 1 portion of the drive cycle for 2010 baseline vehicles and 10% for 2020-2025 is crude, arbitrary, and treats only one of many problems with the driving simulation in the test cycles. Test cycle difficulties carry over into the simulation of hybrid control strategies.
Results		6	1	Sawyer	It is conceivable that BEVs and PHEVs (and less likely FCEVS) will be a significant part of the 2020-2025 vehicle fleet. That they are excluded from the model is a deficiency.
Results		446	2	Sawyer	Lymburner, J.A., et al., Fuel consumption and NOx Trade-offs on a Port-Fuel-Injected SI Gasoline Engine Equipped with a Lean NOx Trap, 4 Aug 09, 20 p. This technical paper examines the trade-off between NOx control and CO2 emissions. Comment: Good work but relevance not clear.
Results		447	2	Sawyer	Lotus(?), (from Kapus, P.E. et al., May 2007), Comparison to other downsized engines This one figure is a partial engine map with context vague. Comment: Significance is not clear.
Completeness	4.4 Transmission Technologies	136	1	McBroom	What types of CVT's were in the original mix? Toroidals, push-belts, Miller?
Completeness	4.4.1 Automatic Transmission	138	1	McBroom	No logical explanation for the 20-33% improvement…how was this number arrived at?

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Completeness	4.4.10 Super Finishing	140	1	McBroom	How much improvement is attributed to super finishing?
Completeness	4.4.3 Wet clutch	139	1	McBroom	It said these were expected to be heavier, cost more and be less efficient than DCT's so why where they included?
Completeness	4.5 Vehicle Technologies	141	1	McBroom	No values for mass, rolling resistance or drag given. No discussion of the improvement possibilities. This would be a good place to use historical trends for vehicle mass reduction, aero improvements and parasitic loss improvement.
Completeness	5.2 Vehicle Configuration and technology combinations	142	1	McBroom	While the tables show the vehicle configurations, more discussion regarding the selection criteria for each vehicle is warranted. In some cases this discussion was attempted in the technology sections, but I don't think it should go there.
Completeness	6.8 Hybrid Models	145	1	McBroom	Too much data is missing. What were the pack voltages? What were the battery technologies? Was there only one or more? Other than improved resistance, what other future improvements were included, like improved power density, improved usable SOC range? What was the control strategy for each type?
Completeness	Section 2 Objectives	122	1	McBroom	A discussion of appropriate/anticipated use of the results is required.
Completeness	Section 3.3 Ground Rules	123	1	McBroom	How did the group arrive at the seven vehicles? While it show comprehensiveness, it's possible to see that there could be some overlap. If one looks at the engine and transmissions packages available in these vehicles already you can see the overlap. Reducing the number of vehicles might save on the number of runs you'll need to make.
Completeness	Section 3.3 Technology Selection Process	124	1	McBroom	Who is on the Advisory Committee? Is it independent? How did the program team come up with the comprehensive list of potential technologies? (From the phone call it sounded like it was based on what models Ricardo (2011) had in their library. This is concerning.)
Completeness	Section 4. Technology Review and Selection	127	1	McBroom	Regarding qualitative evaluation of technology "Potential of the technology to improve GHG emissions on a tank to wheels basis", since this was a qualitative assessment I think it would be better to include well to wheels.
Completeness	Section 4.1.2 DI Fuel Systems	131	1	McBroom	No discussion of DI control strategy. How was it selected? Was there a separate optimization of DI control or was it one size fits all?
Completeness	Section 4.1.3 Boosting Systems	132	1	McBroom	It says that other boosting systems were included in the study, but only turbocharging is discussed.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Completeness	Section 4.3 Hybrids	133	1	McBroom	Don't see any data on the battery technology, battery management, SOC control strategies. No discussion of regen braking strategies.
Completeness	Section 4.3.1 Micro Hybrids	134	1	McBroom	It is implied that electrified accessories aren't used in this configuration. I don't see that as the case.
Completeness	Section 4.3.2 P2 Hybrid	135	1	McBroom	No discussion of why DCT was only transmission used for P2 hybrids instead of CVT and AMT.
Completeness	Section 6 Vehicle Models	143	1	McBroom	No discussion of how driveline inertia is handled. This is important in forward-looking models.
Completeness	Sections 4.1 and 4.2	130	1	McBroom	There's no descriptions of the models. There are only descriptions of the technologies and their perceived benefits. The reader has to assume that the same modeling approach was used to model each technology, but I know from personal experience this is very difficult and most likely not the case.
Completeness		47	1	Assanis	Some of the aspects lacking form the report have already been mentioned and discussed in the relevant sections.
Completeness		48	1	Assanis	In general, the report provides a fair description of the modeling process. Unfortunately, there are no equations, plots or maps showing any specific modeling item, thus making this part of the report vague.
Completeness		49	1	Assanis	It might be possible to shorten the descriptions related to the individual technologies implemented and their improvements and add more details on how they have been modeled. People using this tool will most likely not use the brief descriptions of the various technologies to draw conclusions and make decisions.
Completeness		50	1	Assanis	The "Conclusions" section of the report should be renamed "Summary" since it does not present any actual conclusions based on the results, but it does provide a summary of the project.
Completeness		125	1	McBroom	It said there was a comprehensive list of technologies that the group started with, that list should be shown and a comment on why it wasn't included.
Completeness		126	1	McBroom	Why wasn't HCCI technology considered? From the publications this seems to be a candidate for production in the next 10 yrs.
Completeness		128	1	McBroom	Regarding "Current (2010) maturity of the technology", how was maturity ranked?

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Completeness		129	1	McBroom	Citations required for statement " SI engine efficiency to approach CI efficiency in the time frame considered" This represents relatively large gains in SI technology compared to CI, however EU and Japanese engine companies are making big improvements on CI as well.
Completeness		137	1	McBroom	No transmission data was shown. No mass, no inertia to efficiency maps, no gear ratios.
Completeness		144	1	McBroom	There are several types of rolling resistance models, what type was used?
Completeness		146	1	McBroom	Load leveling the engine by charging the batteries has been shown to not be a very good idea because the round trip efficiency hit is a killer. Should only be used when SOC falls below a certain level.
Completeness		147	1	McBroom	We're left to assume that SOC leveling is accomplished, but there is no description of how? Was an EPA/SAE method used.
Completeness		148	1	McBroom	When it comes to GHG reductions why weren't plug-in hybrids considered?
Completeness		418	2	McBroom	Hybrid: Ricardo (2011) asserts that electric machine design activities of the future will most like concentrate around cost reductions; however I see machine efficiency dropping in order to meet cost reductions. Therefore I think it premature to assume that efficiency will stay the same and cost will drop.
Completeness		299	1	Midlam-Mohler	Based on the above, it is clear that this reviewer feels the report is inadequate at describing the entire process of modeling work from input selection to results. There was not a single subsystem that was documented at the level desired. It is understood that, in some cases, there are things of a proprietary nature that must be concealed. As a trivial example, the frontal area of the vehicle classes does not seem to be anywhere in the report or data analysis tool. This is one parameter amongst hundreds excluding the real details of the models (i.e. equations or block diagrams), methods used to generate engine maps, details on control laws, etc. On the topic of proprietary data, there are many ways of obscuring data sufficiently that can demonstrate a key point (i.e. simulation accuracy) without compromising confidentiality of data – this should not be a major barrier to providing some insight into the inner working of the simulator.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Completeness		7	1	Sawyer	The selection of drivetrain technologies (other than the electric storage technologies) is comprehensive. The qualitative description of the drivetrain technologies is complete and clear, but quantitative performance data are missing. Transparency in the actual performance data is entirely lacking. This includes engine performance maps, shift strategies, battery management in hybrids, and more. That much of that data is proprietary to the companies that generated it and/or to Ricardo (2011) is a problem for what is proposed as a regulatory tool.
Completeness		8	1	Sawyer	The assumptions are difficult to extract from the text.
Completeness		427	2	Sawyer	Ricardo, Assessment of Technology Options, Technologies related to Diesel Engines, 23 Nov 09, 17 p. Overview predicts continuation of low uptake in the U.S. LDA and LDT markets. Review deals with various engine technologies to improve efficiency. Individual improvements <1-5%. Most promising is electric turbo-compounding (bottoming cycle to recover exhaust thermal energy to produce electricity).Comment: Individual technology assessments seem reasonable. There is no analysis of integrating several technologies.
Completeness		433	2	Sawyer	Ricardo, Future Engine Friction Assessment—Response to Action Item Question SI Engine #4, 18 Feb 11, 4 p. (proprietary) Projects continued reduction in engine friction, 2010--2020. Comment: Data provide confirm projection.
Completeness		434	2	Sawyer	Ricardo, Revised Follow--up Answers to 8 April 2010 Meeting with EPA and Ricardo, 19 Apr 10, 8 p. (proprietary) Presents fueling maps for several technologies. Comment: Adds to documentation of engine map data.
Completeness		435	2	Sawyer	Alger, T., Southwest Research Institute, Examples of HEDGE Engines, 2009, 4 p. Presents engine map for a 2.4 L I4 High--Efficiency Dilute Gasoline Engine (HEDGE) engine and compares with TC GDI engine, diesel engine. Comment: Adds to documentation of engine map data.
Completeness		436	2	Sawyer	Ricardo, Hybrid Controls Peer Review, 18 Feb 10, 31 p. (proprietary) Review of hybrid control technologies for various architectures. Review of battery operation in cold weather. Comment: Thorough description of technologies and their operation characteristics. Battery discussion covers similar material to an earlier paper.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Completeness		438	2	Sawyer	Ricardo, Simulation Input Data Review, 4 Feb 10, 14 p. (proprietary) Described hybrid architectures with emphasis on machine-inverter combine efficiencies, including efficiency maps. Comment: More data, seems reasonable.
Completeness		442	2	Sawyer	Trapp, C., et al., NOx emission control options for the Lean Boos downsized gasoline engine, (2 Feb 07), 34 p. Paper compares lean NOx trap and selective catalytic reduction technologies. Includes some engine map data for NOx emissions. Includes cost data for aftertreatment. Comment: Good academic paper with useful data. Not clear what or how Ricardo (2011) used.
Completeness		443	2	Sawyer	Trap, C., et al., NOx emission control options for the lean boost downsized gasoline engine, (2 Feb 07), 27 p. Paper review international emissions regulation and technologies to meet. Comment: This paper contains some of the same information as the preceding two. Simulated date presented, again for SCR and LNT technologies.
Completeness		448	2	Sawyer	Turner, J.W.G., et al. (2009), Sabre: a cost-effective engine technology combination of high efficiency, high performance and low CO2 emissions, Low Carbon Vehicles, May 09, IMechE Proceedings, 14 p. This paper describes a technology for reducing COs emissions in a downsized engine. The Sabre engine is a collaboration between Lotus Engineering and Continental Automotive Systems. Comment: Limited performance data provided.
Completeness		450	2	Sawyer	Ricardo, Report on light-duty vehicle technology package optimization, 4 Dec 09, 32 p. This is a progress report on Ricardo's modeling work for the EPA. A range of engine technologies, hybrid technologies, transmission, and vehicle technologies are described.Comment: A comprehensive list of near term technologies are included. The report is incomplete and optimization apparent is not included here.
Completeness		452	2	Sawyer	Ricardo, Response to questions regarding the generation of the diesel fuel maps for fuel efficiency simulation, 16 Feb 10, 10 p. (proprietary) Paper answers a series of EPA questions on how the diesel fuel maps were generated. Comment: This is relevant information and provides a convincing description of the technical basis for the diesel fuel maps.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Completeness		454	2	Sawyer	Ricardo, SCR as an Enabler for Low CO2 Gasoline Applications, no date, 35 p. This presentation describes technology and implementation for exhaust NOx reduction for lean burn gasoline engines. Comment: Comprehensive discussion of technology, but if and how inconcorporated in the model not clear.
Completeness		455	2	Sawyer	Ricardo, Simulation Input Data Review, 18 Mar 10, 17 p. (proprietary) This document reviews the engine maps used in the model. Includes are examples of the baseline maps plus modifications associated with a range of technologies. Data apply to all 7 vehicle classes. Comment: This is the documentation that was missing in the earlier review material. Looks reasonable and is reassuring.
Completeness		457	2	Sawyer	Shimizu, R., et al., Analysis of a Lean Burn Combustion Concept for Hybrid Vehicles, 2009, 13 p. A technical paper, this document describes early (1984) and more recent Toyota lean burn engines. Comment: Interesting technical description but no clear if or how used in the Ricardo (2011) model.
Completeness		461	2	Sawyer	Kapus, P., Potential of VVA Systems for Improvement of CO2 Pollutant Emission and Performance of Combustion Engines, 30 Nov 2006, 9 p. This is a technical paper describing variable valve actuation approaches and performance effects. Comment: Useful general technical information.
Completeness		223	1	Wade	Concern: This report has significant deficiencies in its description of the entire process used in the modeling work. Many of these deficiencies have been previously discussed, but are listed here for completeness.
Completeness		224	1	Wade	An overall schematic and description of the powertrain and vehicle models and the associated subsystem models/maps were not provided. Only vague descriptions were included in the text of the report.
Completeness		225	1	Wade	Technical descriptions of how the subsystems and vehicle models/maps for the baseline vehicles were developed were not provided.
Completeness		226	1	Wade	None of the overall or subsystem models/maps were provided for review so comments on their adequacy are not possible.
Completeness		227	1	Wade	Most importantly, only minimal descriptions were provided of how each of the advanced technology subsystem models/maps was developed.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Completeness		228	1	Wade	Descriptions of the algorithms used for engine control, transmission control, hybrid system control, and accessory control were not provided.
Completeness		229	1	Wade	Descriptions of how synergistic effects were handled were not provided.
Completeness		230	1	Wade	There are many engine technologies that have potential for reduced GHG emissions that were not included in this study, such as:-Single stage turbocharged engines - Diesel hybrids-Biofueled spark ignition and diesel engines-Natural gas fueled engines- Other alternative fuel engines-Charge depleting PHEV and EV
Recommendations	Accessory load assumptions	338	1	Midlam-Mohler	Cite and/or validate the alternator efficiency values of 55% and 70%.
Recommendations	Accessory load assumptions	339	1	Midlam-Mohler	Account for charge/discharge losses in the advanced alternator control and/or describe the 12V battery model used for the simulation.
Recommendations	Accessory load assumptions	340	1	Midlam-Mohler	Describe, cite, and validate the accessory fan model used in the simulation.
Recommendations	Accessory load assumptions	341	1	Midlam-Mohler	Justify the use of a 200 Amp advanced alternator across all of the vehicle platforms.
Recommendations	Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness	240	1	Wade	Recommendation: Since the baseline vehicles modeled were 2010 production vehicles, the models/maps for the subsystems used in these vehicle models should be included in the report before it is released.
Recommendations	Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness	241	1	Wade	Recommendation: A baseline model of a hybrid vehicle should be developed and compared to 2010 EPA fuel economy test data for production hybrid vehicles.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Recommendations	Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness	242	1	Wade	Recommendation: The detailed assumptions showing how the benefits of dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants were added to the transmission maps should be added to the report before it is released.
Recommendations	Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness	243	1	Wade	Recommendation: Subsystem models/map should be added to this report and another peer review conducted to assess their adequacy before this report is released.
Recommendations	Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness	244	1	Wade	Recommendation: To establish the adequacy of the subsystem models/maps, derivation details should be provided.
Recommendations	Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness	245	1	Wade	Recommendation: Both mechanically driven and electrically driven accessory power requirements should be clearly provided in the report.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Recommendations	Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness	246	1	Wade	Recommendation: A default weight increase/decrease should be added for each technology. If weight reductions are to be studied, then the user should have to input a specific design change, with the appropriate weight reduction built into the model, rather that having an arbitrary slider for weight.
Recommendations	Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness	247	1	Wade	Recommendation: A closer examination of the reasons for the up to 11% discrepancies between the models and baseline vehicles' fuel economy test data should be undertaken so that the models could be refined to provide better agreement.
Recommendations	Advanced Valvetrains (Section 4.1.1)	319	1	Midlam-Mohler	Describe how variable valve timing technologies were applied to the base engine maps.
Recommendations	Advanced Valvetrains (Section 4.1.1)	320	1	Midlam-Mohler	Describe the process of determining the extent of the efficiency improvement.
Recommendations	Advanced Valvetrains (Section 4.1.1)	321	1	Midlam-Mohler	Describe how optimal valve timing was determined across the variety of engines simulated.
Recommendations	Aftertreatment/ Emissions Solutions	316	1	Midlam-Mohler	Provide better evidence that powertrain packages have credible paths to meet emissions standards.
Recommendations	Aftertreatment/ Emissions Solutions	317	1	Midlam-Mohler	Provide evidence that fuel enrichment strategies are consistent with emissions regulations.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Recommendations	Boosting System (4.1.3 and 6.3)	327	1	Midlam-Mohler	Describe the process of arriving at the boosted engine maps.
Recommendations	Boosting System (4.1.3 and 6.3)	328	1	Midlam-Mohler	Describe how factors like knock are addressed in the creation of these maps.
Recommendations	BSFC Map Comparisons	396	2	Midlam-Mohler	I reviewed this but do not have any substantive comments. All of the figures compare pseudo-virtual engines with other pseudo-virtual engines. A comparison back to a known, experimentally validated engine current engine would have been more useful for me as it would allow one to see the magnitude of improvements that were assumed for the 2020 engines and where on the map these improvements were made.
Recommendations	Direct Injection Fuel Systems	323	1	Midlam-Mohler	Cite sources of data used to predict DI performance.
Recommendations	Direct Injection Fuel Systems	324	1	Midlam-Mohler	Describe how this data was used to develop the future engine performance maps.
Recommendations	Direct Injection Fuel Systems	325	1	Midlam-Mohler	Provide validation of modeling techniques used.
Recommendations	Electric Traction Components	353	1	Midlam-Mohler	Describe the method used to model electric traction components.
Recommendations	Electric Traction Components	354	1	Midlam-Mohler	Provide validation/basis for the process used to generate future technology versions of these components.
Recommendations	Electric Traction Components	355	1	Midlam-Mohler	Describe the technique used to scale these components.
Recommendations	Engine Downsizing	330	1	Midlam-Mohler	Properly document the process of scaling engines.
Recommendations	Engine Downsizing	331	1	Midlam-Mohler	Validate the process used to scale engines.
Recommendations	Engine Models	310	1	Midlam-Mohler	Provide fuel and efficiency map data for all engines used in simulation.
Recommendations	Engine Models	311	1	Midlam-Mohler	Describe what the “other inputs” are to the engine maps.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Recommendations	Engine Models	312	1	Midlam-Mohler	Provide specific references of which published data was used to predict performance of the future engines. Some references are given, however, it is not clear how exactly these references are used.
Recommendations	Engine Models	313	1	Midlam-Mohler	Wherever possible, provide validation against data on similar technologies.
Recommendations	Engine Models	314	1	Midlam-Mohler	Describe in detail the approach used to “stack up” technologies for a given powertrain recipe.
Recommendations	Engine technology selection	343	1	Midlam-Mohler	Describe in greater detail the approach used to model technology stack-up on the advanced vehicles.
Recommendations	Engine technology selection	344	1	Midlam-Mohler	Provide some form of validation that this approach is justified.
Recommendations	HEV Battery Model	357	1	Midlam-Mohler	Describe the method used to model the HEV battery.
Recommendations	HEV Battery Model	358	1	Midlam-Mohler	Provide validation/basis for the process used to generate future technology versions of the battery.
Recommendations	HEV Battery Model	359	1	Midlam-Mohler	Describe the technique used to scale the HEV battery .
Recommendations	Hybrid Controls Presentations	400	2	Midlam-Mohler	Several hybrid controls presentations were provided, however, it was difficult to piece together what information superseded the other since they were provided out of context. There were several good slides showing dynamic programming results of different control scenarios, however, it is assumed that this was not used for the mass simulation since it would be computationally impractical. Thus, I expected to see some results comparing the offline control results to the actual control used in the vehicle simulation, however, this was not found. The major concern in this area is developing a control strategy that is near optimal for a wide variety of hybrid architectures as well as architectures with varying component types and sizes. Without further validation in this area it is not clear that the hybrid results are valid since the control has such an important role in this.
Recommendations	Hybrid technology selection	349	1	Midlam-Mohler	Better describe the hybrid control strategy and validate against a current production baseline vehicle.
Recommendations	Hybrid technology selection	350	1	Midlam-Mohler	Validate that the HEV control algorithm performs equally well on all vehicle classes.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Recommendations	Hybrid technology selection	351	1	Midlam-Mohler	Validate that other vehicle performance metrics, like emissions and acceleration, are not adversely impacted by an algorithm that focuses solely on fuel economy. The emission side of things will challenge to validate with this level of model, however, some kind of assurance should be made to these factors which are currently not addressed at all.
Recommendations	Overall recommendations	232	1	Wade	Overall Recommendation: Provide all vehicle and powertrain models/maps and subsystem models/maps used in the analysis in the report so that they can be critically reviewed.
Recommendations	Overall recommendations	233	1	Wade	Overall Recommendation: Expand the technology "package definitions" to enable evaluation of the individual effects of a variety of technologies.
Recommendations	Specific recommendations for improvements	234	1	Wade	Provide an overall schematic and description of the powertrain and vehicle models. a. Show all of the subsystem models/maps used in the overall model. b. Show the format of the information in each of the subsystem models (including input, subsystem model, output).
Recommendations	Specific recommendations for improvements	235	1	Wade	Provide technical descriptions of how the subsystems and vehicle models/maps for the baseline vehicles were developed.
Recommendations	Specific recommendations for improvements	236	1	Wade	Provide overall system and subsystem models/maps in the report.
Recommendations	Specific recommendations for improvements	237	1	Wade	Provide detailed technical descriptions of how each of the advanced technology subsystem models/maps was developed.
Recommendations	Specific recommendations for improvements	238	1	Wade	Provide descriptions of the algorithms used for engine control, transmission control, hybrid system control, and accessory control.
Recommendations	Specific recommendations for improvements	239	1	Wade	Provide detailed descriptions of how synergistic effects were handled.
Recommendations	Transmissions	361	1	Midlam-Mohler	Cite data sources used in modeling.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Recommendations	Transmissions	362	1	Midlam-Mohler	Validate models wherever possible.
Recommendations	Transmissions	363	1	Midlam-Mohler	Fully describe transmission models/maps and processes used to generate them.
Recommendations	Transmissions	364	1	Midlam-Mohler	Fully describe clutch/torque converter models/maps and processes used to generate them.
Recommendations	Transmissions	365	1	Midlam-Mohler	Fully describe the process used to generate shift maps and the operation of the shift controller.
Recommendations	Transmissions	366	1	Midlam-Mohler	Fully describe the lockup controller (i.e. how soon can it enter lockup after shifting?).
Recommendations	Transmissions	367	1	Midlam-Mohler	Fully describe the process for modeling torque holes during shifting.
Recommendations	Transmissions	368	1	Midlam-Mohler	Fully describe the model used for the final drive (i.e. inputs/structure/outputs).
Recommendations	Vehicle model issues	304	1	Midlam-Mohler	List the dynamic equation describing the longitudinal motion of the vehicle.
Recommendations	Vehicle model issues	305	1	Midlam-Mohler	List all parameters used for each vehicle class for simulation.
Recommendations	Vehicle model issues	381	2	Midlam-Mohler	List the dynamic equation describing the longitudinal motion of the vehicle a. NOT ADDRESSED IN SUPPLEMNTAL MATERIAL REVIEWED
Recommendations	Vehicle model issues	382	2	Midlam-Mohler	List all parameters used for each vehicle class for simulation a. NOT ADDRESSED IN SUPPLEMNTAL MATERIAL REVIEWED
Recommendations	Warm-Up Methodology	333	1	Midlam-Mohler	Cite sources of data for 10% and 20% factors applied to the cold bag fuel economy data.
Recommendations	Warm-Up Methodology	334	1	Midlam-Mohler	Cite and/or validate the modeling approach used.
Recommendations		51	1	Assanis	Various suggestions have already been included in the relevant sections.
Recommendations		52	1	Assanis	The authors should expand the modeling sections. In particular, they should cite literature references (where possible) and provide more detail when empirical data, modifiers, or

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
					scaling laws are used.
Recommendations		53	1	Assanis	Flexibility should be added to the models. Some engine technologies, such as variable cam phasing, HCCI and alternative fuels should be considered.
Recommendations		54	1	Assanis	A self-contained study should be presented as a test case for the results so that specific conclusions can be drawn and the utility of the approach more easily understood.
Recommendations		149	1	McBroom	Instead of using proprietary Ricardo (2011) data/models/control algorithms citable data should be used.
Recommendations		150	1	McBroom	Without stating how this model is going to be used in the regulatory decision making process, it is very difficult to assess its appropriateness.
Recommendations		151	1	McBroom	Considerably more time in this effort is required up front in the report, to discuss the process of building consensus on data and models. Because this is not really discussed, it gives the impression that not much was done.
Recommendations		152	1	McBroom	Guidelines for appropriate use should be given.
Recommendations		153	1	McBroom	An uncertainty rating for each model/data set should be published to highlight the relative differences in the assumptions/extrapolation of future technologies.
Recommendations		154	1	McBroom	Should use coast down data for baseline vehicles to model parasitic losses.
Recommendations		155	1	McBroom	In terms of acceptable use: rather that trying to use the model to assess the boundaries of the envelope (or which technology is better), the tool could be used to find the areas of maximum overlap. In other words, knowing that the same performance and fuel economy is achievable using different technologies lends more confidence that the result is achievable. Theoretically this number could be a calculated value generated from the RSM's.
Recommendations		156	1	McBroom	Recommend allowing "real world" drive cycles to assess the robustness of the results. Could be a user generated result from a composite of the data sets already generated.
Recommendations		157	1	McBroom	Should define the process for data selection….eventually you'll be asked by a manufacturer, 'how do we get 'x' technology included for consideration in the study.
Recommendations		158	1	McBroom	Where lumped improvements are made, I recommend using historical results to publish technology improvement curves. For example, the parasitic losses (Cd, Crr) should be quantifiable. Vehicle mass reductions as well.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Recommendations		300	1	Midlam-Mohler	Given the low level of detail given in the report, it does seem that the strategy used is consistent with the goal of the work and what others in the field are doing. That being said, the report is inadequate in nearly every respect at documenting model inputs, model parameters, modeling methodology, and the sources and techniques used to develop the technology performance data. Given the need for transparency in this effort, this reviewer feels that the detail in the report is wholly inadequate to document the process used. The organization responsible for the modeling has expertise in this area it is certainly possible that the methodology is sound, however, given just the information in the report there is simply no way for an external reviewer to make this conclusion.
Recommendations		301	1	Midlam-Mohler	Because of the lack of hard information to answer the charge questions, this peer review evolved mainly into a suggested list of details that should be brought forward in order to allow the charge questions to be answered properly. With this information, it is hoped that a person with expertise in the appropriate areas will be able comment on the work more fully.
Recommendations		9	1	Sawyer	The failure to model the drivetrain-weight interactions is a major shortcoming. Appendix 2 should clearly state that vehicle weights are held constant (assuming that I am correct in that assumption).
Recommendations		10	1	Sawyer	There should be a table describing the baseline vehicles.
Recommendations		11	1	Sawyer	Summarizing assumptions in tabular form would be a great assistance to the reader.
Recommendations		12	1	Sawyer	The design space should be expanded to include performance parameters, such as power/weight or 0-60 times.
Recommendations		423	2	Sawyer	Ricardo, BSFC Map Commparisons, LBDI vs EGR Boost & DVA for STDI, OBDI, & EGR Boost, Light Duty Vehicle Complex Systems Simulation, EPA Contract No. EP-W=07=064, work assignment 2-2, 24 Feb 10, 20 p. (proprietary) Comparison of engine technologies in terms of maps of percent difference in bsfc in bmep vs rpm space allows visualization Comment: Straight forward data analysis, presumably as requested by USEPA. Should aid in understanding technology performance differences.
Recommendations		426	2	Sawyer	Ricardo, Response to EPA Questions on the Diesel Engine Fuel Maps, Supplemental Graphs for Word Document, 16 Feb 10, 11 p. (proprietary) Document presents proposed diesel engine maps for MY2020+ vehicles. Comment: Anticipated technologies are listed but how the maps were generated is not described. Maps seem reasonable.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Recommendations		431	2	Sawyer	Odvarka, E., et al., Electgric motor--generator for a hybrid electric vehicle, Engineering Mechanics, 16, 131--139, 2009, 9 p. Describes electrical machine options of hybrid electric vehicles. Includes efficiency maps for four technologies. Comment: Data are of general interest, but date from 2003.
Recommendations		444	2	Sawyer	Ricardo, Lean/Stoichiometric switching load for 2020 Hybrid Boost Concept, (no date), 2 p. Presents space velocity and fuel maps. Comment: Relevance not clear.
Recommendations		445	2	Sawyer	Ricardo, Proposed Lean/Stoichiometric switching load for hybrid boost concept, 29 Apr 10, 1 p. Identifies proposed lean zone operating region on engine map. Comment: relevance not clear.
Recommendations		460	2	Sawyer	Ricardo, Transient Performance of Advanced Turbocharged Engines, 15 Sep 10, 19 p. (proprietary) This report reviews expected advances in boosting technologies and anticipated effects on vehicle performance. Comment: Interesting information but how it impacts model is not clear.
Recommendations		231	1	Wade	This report needs major enhancements to reach the stated goal of being open and transparent in the assumptions made and the methods of simulation. Recommendations to rectify the deficiencies in these areas are provided in the previous four items.
Executive Summary		295	1	Midlam-Mohler	For the purpose of describing the modeling approach used in the forecasting of the performance of future technologies, the report reviewed is inadequate. In virtually every area, the report lacks sufficient information to answer the charge questions provided for the reviewer. It is entirely possible that the approach used is satisfactory for the intended purpose. However, given the information provided for the review, it is not possible for this reviewer to make any statement regarding the suitability of this approach.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Executive Summary		383	2	Midlam-Mohler	The supplemental review material provided some answers to questions posed above, but in general, did not provide the level of detail necessary to ensure a thorough review of the process. The conclusion of this reviewer remains similar as on the original review, which is that there were no serious flaws found in the work, however, there were enough omissions that it is not possible to accurately judge if the predictions made are accurate. The biggest concern in this work is the lack of validation and/or citation of where data and models are coming from. There are numerous maps that are presented in the follow-up material, however, these maps had to have originated from some process (which needs documented) and should be compared against some kind of validation. Despite the lack of documentation provided, the work is generally that of a project team that is competent in this field of study.
Executive Summary		463	2	Sawyer	Ricardo (2011) has provided material, which is stated to be the data incorporated in the computer simulation. These data are consistent with the data expected to be the basis of the simulation. It is impossible to establish a precise correspondence between the data and the model. The performance data covered by the 44 separate documents seem reasonable and provide additional assurance that the simulation is soundly based on measured performance. There is no reason to doubt either the integrity or capability of Ricardo (2011) in their incorporation of appropriate data into their simulation model.
Other Comments	Accessory Models	269	1	Wade	None of the accessory models were not provided for review, so their adequacy and suitability cannot be assessed.
Other Comments	Accessory Models	270	1	Wade	The accessory loads vs. engine speed for the conventional belt driven accessories were apparently removed from the engine when electric accessories were applied. However, the conventional accessory loads as well as the alternator loads/battery loads for the electric accessories were not provided.
Other Comments	Accessory Models	271	1	Wade	In contrast, as an example, PQA and Ricardo (2008) provided the following map of an electric water pump and AC compressor drive efficiency. Similar maps for all accessory models would be expected in this report. (See Exhibit 6)

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments	Advanced Valvetrains (Section 4.1.1)	56	1	Assanis	The report states that advanced valvetrain systems improve fuel consumption and GHG emissions mainly by improving engine breathing. Other benefits cited are in supporting engine downsizing and faster aftertreatment warm-up. Beyond improving volumetric efficiency and reducing pumping losses, advanced valvetrains can enable compression ratio variation to increase fuel economy and avoid knock, alter the combustion process by modulating trapped residual, and enable cylinder deactivation to reduce pumping losses. From the report, it is not clear which of the possible benefits of the advanced valvetrain packages have been harnessed in each case. A more systematic analysis of technology package combinations is warranted as several are synergistic but not additive.
Other Comments	Boosting System (4.1.3 and 6.3)	57	1	Assanis	A two-stage system is indeed promising for advanced turbocharging concepts. A distinction should be made between series and sequential configurations. Air flow manipulation can make it a series system (two-stage expansion and compression) or a sequential system (turbos activated at different rpm). Variable geometry or twin-scroll turbines can be good options for the low or high pressure stages, respectively. A two-stage turbocharging system like this would take advantage of the lean SI exhaust enthalpy, reduce pumping work (or even aid pumping), avoid mechanical work penalties, improve engine transient response, enable high dilution levels (if desired) and probably help keep in-cylinder compression ratio below 12:1, since significant compression would be done before the cylinder. EGR flow could be driven through a low pressure loop (after the turbines) or an intermediate pressure loop (between the turbines). The resulting turbo lag will depend on the details of the configuration and the control logic used. Note that the assumption of a time constant of 1.5 seconds (as stated in the report) to represent the expected delay may not hold true in all cases.
Other Comments	Boosting Systems	272	1	Wade	The report states that “various boosting approaches are possible, such as superchargers, turbochargers, and electric motor-driven compressors and turbines.” (page 13). However, elsewhere the report states “series-sequential turbochargers” will be used on the Stoichiometric DI Turbo engine (page 15).
Other Comments	Boosting Systems	273	1	Wade	It is not clear in the report how the series-sequential turbocharger was selected from the variety of boosting devices that were introduced. Models for the turbochargers with compressor and turbine efficiency maps were not provided, so the appropriateness of these model cannot be assessed.
Other Comments	Boosting Systems	274	1	Wade	Comment: The model should include a single turbocharger system with less extreme downsizing as advocated by the Sabre Engine (Coltman et al., 2008; Turner et al., 2009) as a lower cost alternative to series-sequential turbochargers.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments	Cooled Exhaust Manifold	284	1	Wade	The Ricardo (2011) report states, "The future engine configuration was assumed to use a cooled exhaust manifold to keep the turbine inlet temperature below 950C… No explanation was provided of how the limit on turbine inlet temperature would affect boost pressure and power.
Other Comments	Efficient Components (Section 4.4.9)	61	1	Assanis	Efficient components should also include gears since rotating gears are also a major source of drag. Designing a better profile for gear teeth can reduce drag losses.
Other Comments	Engine Models	254	1	Wade	Engine models provided the torque curve, fueling map and other input parameters (which were not specified in the report) (page 25). Since the report stated that "The fueling maps and other engine model parameters used in the study were based on published data and Ricardo (2011) proprietary data (page 26), their adequacy and suitability could not be assessed.
Other Comments	Engine Models	255	1	Wade	The report states that engines used in the model were developed using two main methods (page 14). 1. The first method assumed that "reported performance of current research engines would closely resemble production engines of the 2020-2025 timeframe. 2. The second method began with current production engines and then a "pathway of technology improvements over the new 10-15 years that would lead to an appropriate engine configuration for the 2020-2025 timeframe" was applied.Both of these approaches are reasonable if: 1. appropriate references are provided, 2. the reported performances for the research engines used are documented in the report, 3. the technology improvements are documented in the report, and 4. the methodology of incorporating the improvements is fully documented.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments	Engine Models	256	1	Wade	The description of the derivation of the engine models in the report was, at best, vague, as illustrated by the two examples below: Example 1: Stoichiometric DI Turbo The current research engines of this configuration were reported to be the Sabre engine developed by Lotus and the downsized concept engine developed by Mahle. Since the engine modeled in the Ricardo (2011) report had a peak BMEP of 25-30 bar and used series-sequential turbochargers, the Sabre engine is not applicable since it only had a peak BMEP of 20 bar and used a single stage turbocharger (Coltman et al., 2008; Turner et al., 2009). On the other hand, the Mahle engine appeared to be directly applicable, since it had a peak BMEP of 30 bar and used series-sequential turbocharging (Lumsden et al., 2009). Since Lumsden, et a. (2009) provided the BSFC map for this engine, shown below, it is not clear why the Ricardo (2011) report could not have shown this map, or a map derived from this one, and then described how it was derived and/or combined with other maps to provide the model used in the report. (See Exhibit 3)
Other Comments	Engine Models	257	1	Wade	The description of the derivation of the engine models in the report was, at best, vague, as illustrated by the two examples below: Example 2: Advanced Diesel For the advanced diesel, the report provided the following description: "…the LHDT engine torque curve and fueling maps were generated by starting with a 6.6L diesel engine typical for this class and applying the benefits of improvements in pumping losses or friction to the fueling map". No description of the improvements in pumping losses or friction reduction was provided and the variation of these improvements over the speed and load map were not provided. In addition, the baseline 6.6L engine map was not provided, the 6.6L friction map was not provided and the methodology for applying the improvements to the 6.6L engine map was not provided.
Other Comments	Engine Models	258	1	Wade	The report should explain whether the engine model is only a map of BSFC vs. speed and load, or if the engine model includes details of the turbocharger, valve timing, and control algorithms for parameters such as air/fuel ratio, spark/injection timing, EGR rate, boost pressure, and valve timing.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments	Engine Models	259	1	Wade	Advanced valvetrains were included in many of the advanced engines (page 12). However, the method for applying these advanced valvetrains to the engine maps was not provided. Also, no description of the control strategy for these valvetrains was provided. The report did not provide a description of how the reduction of pumping losses with an advanced valvetrain was applied to a downsized engine that already had reduced pumping losses. Therefore, no assessment of how the model handled synergies could be made.
Other Comments	Engine Models	260	1	Wade	In summary, the Ricardo (2011) report provided insufficient descriptions of the derivation of the maps used for all of the engines in this study, which included: - Baseline - Stoichiometric DI Turbo - Lean-Stoichiometric Switching - EGR DI Turbo - Atkinson Cycle - Advanced Diesel
Other Comments	Engine Scaling	289	1	Wade	The report states, "The BSFC of the scaled engine map is …adjusted by a factor that accounts for the change in heat loss that comes with decreasing the cylinder volume, and thereby increasing the surface to volume ratio for the cylinder" (page 26). This is a directionally correct correction. However, specific values for the correction should be provided, together with references to the data and methodology used to derive the values used.
Other Comments	Engine Scaling	290	1	Wade	Issue: The report states, "…downsizing the engine directly scales the delivered torque, …" (page 26). However, since there will be increased heat loss from the smaller displacement cylinder, the torque would be expected to be less than the directly scaled values for the same fueling rate.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments	Hybrid Technologies Models	265	1	Wade	Key elements of a hybrid system include: electric machines (motor-generator), power electronics, and a high-voltage battery. Only the following vague description of the models for these subsystems was provided: "For each of these systems, current state of the art technologies were adapted to an advanced 2020-2025 version of the systems, such as by lowering internal resistance in the battery pack to represent 2010 chemistries under development and decreasing losses in the electric machine and power electronics to represent continued improvements in technology and implementation" (page 29). This vague description did not provide adequate details to assess the adequacy of these models. For example, specific values for internal resistance with references should be provided together with an illustration of how this was incorporated in the model of the battery.
Other Comments	Hybrid Technologies Models	266	1	Wade	In contrast, as an example, Staunton, et al. (2006) provided a detailed motor efficiency map, shown below, as well as efficiency maps of other key components of the Prius hybrid vehicle. Similar maps for all hybrid subsystems would be expected in this report. (See Exhibit 5)
Other Comments	Hybrid Technologies Models	267	1	Wade	In addition, "a Ricardo proprietary methodology was used to identify the best possible fuel consumption for a given hybrid powertrain configuration over the drive cycles of interest." (page 29), which precluded an assessment of its suitability.
Other Comments	Hybrid Technologies Models	268	1	Wade	No mention was provided of how the cooling system for the hybrid system was modeled.
Other Comments	Lean-Stoichiometric Switching (Section 4.2.2)	58	1	Assanis	The mixed-mode operation considered in the report seems to switch between stoichiometric and lean SI direct injection operation. There are several multi-mode combustion efforts under development that encompass several more combustion modes, including HCCI and Sparkassisted compression ignition with amounts of EGR dilution.
Other Comments	Lean-Stoichiometric Switching Engine	288	1	Wade	The report states that this engine will use a lean NOx trap or a urea-based SCR system (page 15). The use of fuel as a reducing agent was also suggested in the report (page 16). However, the fuel economy penalty associated with regenerating the NOx trap or the reducing agent for the SCR system was not provided.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments	P2 Parallel Hybrid (Section 4.3.2)	59	1	Assanis	P2 refers to pre-transmission parallel hybrid, where an electric machine is placed in between the engine and the transmission. While the report does not discuss details, there are two possible configurations: (i) a single clutch, located in between the engine and the electric machine, such as in the Hyundai Sonata, and (ii) two clutches, one in between the engine and the motor, and the other one in between the motor and the transmission, such as in the Infiniti M35 HEV. The P2 system looks promising to achieve good efficiency, but remaining barriers include cost, drive quality, durability and to a lesser extend packaging. Careful consideration of details is needed to properly assess benefits compared to a single mode power split. Early reports have indicated that Nissan got 38% mpg increase out of their P2 and Hyundai got 42%, both with higher horsepower, as well. However, the P2 Touareg doesn't seem to meet EPA 2012 CAFE standards.
Other Comments	Stoichiometric DI Turbo Engine	275	1	Wade	The table below compares several attributes of the Ricardo Stoichiometric DI Turbo Engine with the Mahle Turbocharged, DI Concept Engine. (See Exhibit 7)
Other Comments	Stoichiometric DI Turbo Engine	276	1	Wade	Key content of the Mahle Turbocharged, DI Concept Engine: - Two turbochargers in series - Charge air cooler - Dual variable valve timing - High energy ignition coils - Fabricated, sodium cooled valves - EGR cooler
Other Comments	Stoichiometric DI Turbo Engine	277	1	Wade	Lumsden, et al. (2009) describing the Mahle concept engine stated that lowest fuel consumption that usually occurs around 2000 rpm had moved out to 4000 rpm for the series-sequential turbocharged engine.
Other Comments	Stoichiometric DI Turbo Engine	278	1	Wade	Issue: The Ricardo (2011) report did not discuss the concern that the lowest fuel consumption in a series-sequential turbocharged engine had moved out to 4000 rpm, rather than the usual 2000 rpm and did not discuss how this concern was handled.
Other Comments	Stoichiometric DI Turbo Engine	279	1	Wade	The foregoing table indicates several significant issues: 1. The turbine inlet temperature of the Mahle engine is significantly higher than the limit assumed for the Ricardo engine (1025C vs. 950C). Reducing the turbine inlet temperature is expected to result in lower BMEP levels where the temperature is limited. (see Exhibit 7)

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments	Stoichiometric DI Turbo Engine	280	1	Wade	The foregoing table indicates several significant issues: 2. The turbocharger response time for the Mahle engine is 2.5 seconds, whereas Ricardo (2011) assumed a time constant of 1.5 seconds. Such turbocharger delays are expected to result in significant driveability issues for engines that are downsized approximately 50%. (see Exhibit 7)
Other Comments	Stoichiometric DI Turbo Engine	281	1	Wade	The table below compares several attributes of the Ricardo Stoichiometric DI Turbo Engine with the Lotus Sabre Engine. (see Exhibit 8)
Other Comments	Stoichiometric DI Turbo Engine	282	1	Wade	The paper on the Sabre engine (Turner et al., 2009) indicates that operation at lower turbine inlet temperatures results in a reduction in BMEP. However, the turbine inlet temperature for the Sabre engine is still 40C above Ricardo's assumption.
Other Comments	Stoichiometric DI Turbo Engine	283	1	Wade	Turner et al. (2009) indicates that the Sabre engine with a single stage turbocharger provides an attractive alternative to extreme downsizing with series-sequential turbochargers.
Other Comments	Transmission Models	261	1	Wade	Similar to engine models, the description of the derivation of transmission models was also vague. Using the automatic transmission model as an example, "For the 2020-2025 timeframe, losses in automatic transmissions are expected to be about 20-33% lower than in current automatic transmissions from the specific technologies described below." The specific technologies that could provide these reductions appeared to include: - Shift clutch technology - to improve thermal capacity of the shifting clutch to reduce plate count and lower clutch losses during shifting. - Improved kinematic design – no description of these improvements was provided. -Dry sump – to reduce windage and churning losses. - Efficient components – improvements in seals, bearings and clutches to reduce drag. - Super finishing - improvements expected were not specified. -Lubrication- new developments in base oils and additive packages, but improvements were not specified.
Other Comments	Transmission Models	262	1	Wade	In addition to not specifying the improvements expected from these technologies, no indication was provided of how these technologies were applied to the transmission models. For example, -The report stated that losses in automatic transmissions are expected to be about 20-33% lower than in current automatic transmissions (page 19). However, the baseline losses were not provided for reference and the means to achieve these reductions were not described. - The report stated that energy losses in DCTs are expected to be 40-50% lower than in current automatic transmissions (page 19). The details of this reduction were not provided and references describing these reductions were not provided.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
					- Bearing and seal losses have a greater effect on efficiency at light loads than at heavy loads. The report did not describe how these losses were incorporated in the model. In contrast to the lack of descriptions of details in the report, PQA and Ricardo (2008), as an example, provided the following map of bearing losses in a transmission as a function of shaft diameter and speed. Similar details for the relevant aspects of the transmission models in this report would have been expected. (See Exhibit 4)
Other Comments	Transmission Models	263	1	Wade	In summary, the Ricardo (2011) report provided insufficient descriptions of the derivation of the maps for the following transmissions:- Advanced automatic- Dry clutch DCT- Wet clutch DCT- P2 Parallel hybrid transmission- PS Power Split hybrid transmission
Other Comments	Transmission Models	264	1	Wade	In addition, the models for the automatic transmissions of the baseline vehicles were not provided, so that their adequacy could not be assessed.
Other Comments	Transmission Models (Section 6.4)	62	1	Assanis	It is claimed that gear selection will be optimized for fuel economy for a given driver input and road load. Can this also be adaptive? Engine performance degrades with age. This strategy could also lead to more gear shifts; the latter would increase hydraulic loads and frictional power losses in the clutch, thus eroding some of the possible fuel economy gains.
Other Comments	Transmission Technologies (Section 4.4)	60	1	Assanis	What about automatic transmissions with automated clutch replacing the torque convertor and lock-up clutch? This is also a possibility.
Other Comments	Warm-Up Methodology	285	1	Wade	"Ricardo used company proprietary data to develop an engine warm-up profile" which was used to increase the fueling requirements during the cold start portion of the FTP75 drive cycle (page 26). Since this data was proprietary, no assessment of its appropriateness can be made.
Other Comments	Warm-Up Methodology	286	1	Wade	Elsewhere the report states, "A bag 1 correction factor is applied to the simulated "hot" fuel economy result of the vehicles to approximate warm-up conditions…" The correction factor reduces the fuel economy results of the FTP75 bag 1 portion of the drive cycle by 20% on the current baseline vehicles and 10% on 2020-2025 vehicles that take advantage of fast warm-up technologies" (page 29). No references or data are cited to support this significant reduction in correction factor.
Other Comments	Warm-Up Methodology	287	1	Wade	Issue: No explanation was provided to clarify when the "engine warm-up profile" is used and when the "correction factor" is used. Therefore, the appropriateness of the warm-up methodology cannot be assessed.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments		15	1	Assanis	The report is intended to provide administrators, product planners and legislators a practical tool for assessing what is achievable, as well as insight into the complexity of the path forward to reach those advances that will be useful for productive discussions between EPA and the manufacturers. This path forward involves trade-offs among many design choices involving available, and soon-to-be-available advances in engine technologies, hybridization, transmissions and accessories. The current version of the simulation effort seems reasonably balanced in the attention paid to each of these areas. The range of improvements shown in the technologies considered and examples is encouraging.
Other Comments		16	1	Assanis	Overall, the project attempts to undertake an analytical technology assessment study of significant scope. It does a fairly competent job at analyzing a select number of technologies and packages, mostly aimed at improving the gasoline IC engine, and to a less extent the diesel engine. It complements improvements on the engine side with synergistic developments on the transmissions, hybrids and accessories. The main shortcoming of the study is that the methodology relies extensively on proprietary and undisclosed data, as well as empirical rules, correlations and modifiers without citing published reference sources. eyond the perceived lack of transparency, keeping up with new technologies or approaches will necessarily involve new versions of the program since the actual models of the technologies used are proprietary and the choice and range of parameters available to users is fixed and to some extent hidden. Due to these constraints, the simulation tool is limited in its ability to provide fundamental insight; this will require a more basic thermodynamic approach, perhaps best carried out by universities.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments		17	1	Assanis	For the most part, the right technologies are being considered. However, certain promising technologies and fuel options for IC engine technologies (other than gasoline and diesel) that can make a significant contribution to the improvement of mpg and reduction of CO2 emissions have not been considered, or even mentioned at all. Primary examples are advanced combustion technologies, such as high pressure, dilute burn, low temperature combustion (e.g., Homogeneous Charge Compression Ignition, Partially Premixed Compression Ignition, Spark-Assisted Compression Ignition), and closed-loop, in-cylinder pressure feedback. Some of these combustion technologies have the potential to improve fuel economy by up to 25%. Another significant assumption is that fuels used are equivalent to either 87 octane pump gasoline or 40 cetane pump diesel. However, advanced biofuels, particularly from cellulosic or lingo-cellulosic bio-refinery processes, which from the standpoint of a life cycle analysis have strong potential for reduction of CO2 emissions, can have significantly different properties (including octane and cetane numbers) and combustion characteristics than the current fuels. Note that over 13 billion gallons of renewables were used in 2010, primarily from corn-ethanol and some biodiesel. According to the Renewable Fuel Standard, 36 billion gallons of renewables need to be used by 2022. Also, a joint study carried-out by Sandia and General Motors has shown that ninety billion gallons of ethanol (the energy equivalent of approximately 60 billion gallons of gasoline) can be produced in the US by year 2030 under an aggressive biofuels deployment schedule.
Other Comments		18	1	Assanis	The report is lengthy at places, for instance in the description of technologies which users of the simulation software are likely to be already familiar with, while too laconic at other places, e.g. how the selected technologies were modeled in some detail. The draft can benefit from better balancing of its sections. There should also be more words summarizing the illustrative results (e.g., provide ranges of benefits), and assessing them critically (e.g., which technologies seem to incrementally or additively contribute the most), rather than just stating that the results are in Table 7.1 or in Appendix 3. A discussion of uncertainties present in the analysis should be presented so as to enable the reader to place the findings into proper perspective.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments		19	1	Assanis	The characterization of the modeling methodology as objective and "scientific" suggests that the simulation is composed of rigorous, first-principle expressions for the various phenomena without using "correlations", "empirical formulas", and "phenomenological models". Are these conditions truly met? For instance, in many cases, steady-state dyno test data are the basis of an engine map featuring a certain technology. In other cases, available data were scaled based onempirical/proprietary factors and modifiers. The report should not characterize the study as "scientific" unless data uncertainty is discussed and shown in appropriate situations. For example, Table 7.1 presents comparisons between simulated and actual vehicle fuel economy performance. Given the various subjective assumptions involved in the analysis, the authors should comment whether the noticeable differences in certain cases are significant.
Other Comments		55	1	Assanis	It would be desirable to show the analysis used to convert fuel consumption savings to vehicle greenhouse gas (GHG) emissions equivalent output. Ultimately, what matters is the GHG savings resulting from the combined production and use cycle of alternative fuel options for combustion engines.
Other Comments		159	1	McBroom	Having conducted a similar effort for USCAR on the PNGV program, I understand that considerable effort is required to develop such a model. I don't want to diminish all the hard work that was done, by only offering criticism in the above sections. It appears that the intent of the approach to this activity is in the right place, just better documentation is needed and appropriate use guidelines.
Other Comments		13	1	Sawyer	The conclusions, Section 11, are a reasonable summary of the work conducted.
Other Comments		14	1	Sawyer	Including the membership of the advisory committee would be appropriate.
Other Comments		429	2	Sawyer	Ricardo, Hybrid Controls Follow-up, 10 Sep 11, 3 p. (proprietary) Report discussed motor/general efficiency map used for 2020 technology. Projected efficiencies peak at 95% but most P2 hybrid application if below 90% efficiency. Comment: I am not qualified to assess if the projected motor/generator efficiencies are appropriate for 2020-2025 as reported, but they seem low for 15 years in the future.
Other Comments		456	2	Sawyer	Ricardo, Assessment of Technology Options, 19 Nov 09, 22 p. (confidential) This document reviews and rates a range of spark-ignition adaptable technologies to reduce CO2 emissions. Biofuels are included. Comment: An interesting compendium but some previously reported.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments		248	1	Wade	The vehicle model and powertrain model were developed and implemented by Ricardo (2011) in the MSC.Easy5 software package. The model reacts to driver input to provide the torque levels and wheel speeds required to drive a specified vehicle over specified driving cycles. The overall model consists of subsystem models that determine key component outputs such as torque, speeds, heat rejection, and efficiencies. Subsystem models are expected to be required for the engine, accessories, transmission, hybrid system (if included), final drive, tires and vehicle, although the report did not clearly specify the individual subsystem models used.
Other Comments		249	1	Wade	A design of experiments (DOE) matrix was constructed and the vehicle models were used to generate selected performance, fuel economy and GHG emission results over the design space of the DOE matrix. Response surface modeling (RSM) was generated in the form of neural networks. The output from each model simulation run was used to develop the main output factors used in the fit of the RSM. The resulting Complex Systems Model (CSM) provides a useful tool for viewing the results from this analysis that included over 350,000 individual vehicle simulation cases.
Other Comments		250	1	Wade	The vehicle and powertrain models/maps and subsystem models/maps used in the analysis were not provided in the report and could not be reviewed. In most cases, the report stated that the models/maps were either proprietary to Ricardo (2011) or at least elements were proprietary so that they could not be provided for review. Without having these models/maps and subsystem models/maps, their adequacy and suitability cannot be assessed.
Other Coments		251	1	Wade	Overall Recommendation: Provide all vehicle and powertrain models/maps and subsystem models/maps used in the analysis in the report so that they can be critically reviewed.
Other Comments		252	1	Wade	The technology “package definitions” preclude an examination of the individual effects of a variety of technologies. For example, for the Stoichiometric DI Turbo engine, only the version with a series-sequential turbocharger could be evaluated whereas a lower cost alternative with a single turbocharger could not be evaluated. Likewise, only the AT8-2020 transmission could be evaluated with the Stoichiometric DI Turbo engine, while the substitution of the AT6-2010, as a lower cost alternative, could not be evaluated.
Other Comments		253	1	Wade	Overall Recommendation: Expand the technology “package definitions” to enable evaluation of the individual effects of a variety of technologies.

Charge Question Topic	Specific Assumption/Topic	Comment Excerpt No.	Review Round	Reviewer	Comment
Other Comments		291	1	Wade	Sample Output From Complex System Model (CSM) 5/4/2011 Relative Percentage Differences Were Added by W. R. Wade (see Exhibit 9)

The peer reviewer Dr. Wade included the following ten exhibits in comments. These are cited in the table of verbatim comments.

Exhibit 1

Parameter	DoE Range (%)	
Engine Displacement	50	125
Final Drive Ratio	75	125
Rolling Resistance	70	100
Aerodynamic Drag	70	100
Mass	60	120

Exhibit 2

Parameter	DoE Range (%) P2 Hybrid		Powersplit	
Engine Displacement	50	150	50	125
Final Drive Ratio	75	125	75	125
Rolling Resistance	70	100	70	100
Aerodynamic Drag	70	100	70	100
Mass	60	120	60	120
Electric Machine Size	50	300	50	150

Exhibit 3

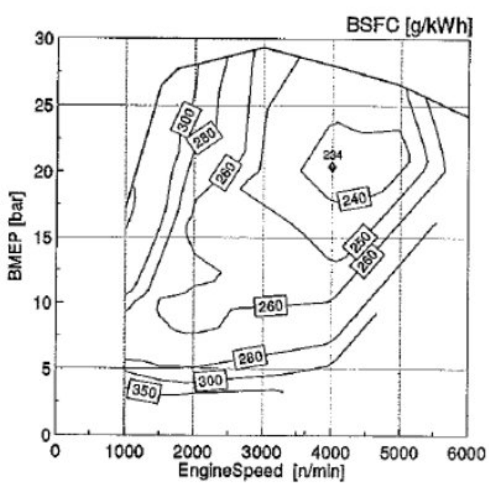

Figure 19: BSFC over the engine operating envelope, CR 9.7:1.

Exhibit 4

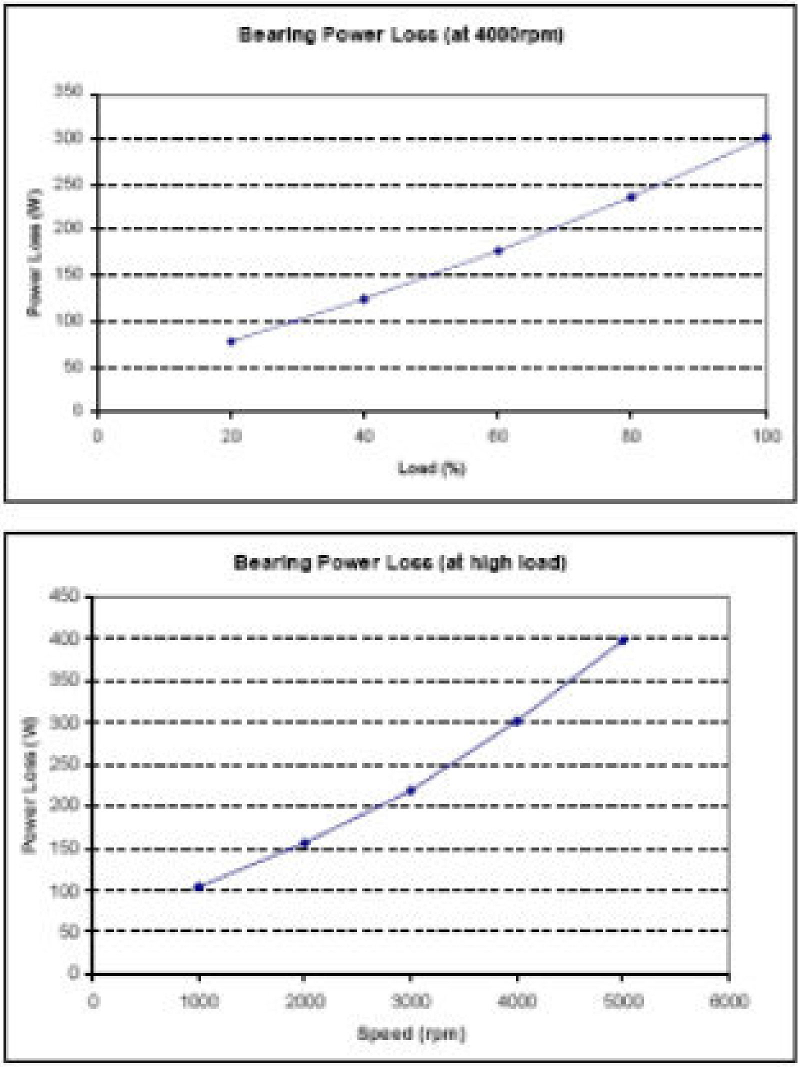

Figure 5-23: Estimated power loss in a deep-groove ball bearing

Exhibit 5

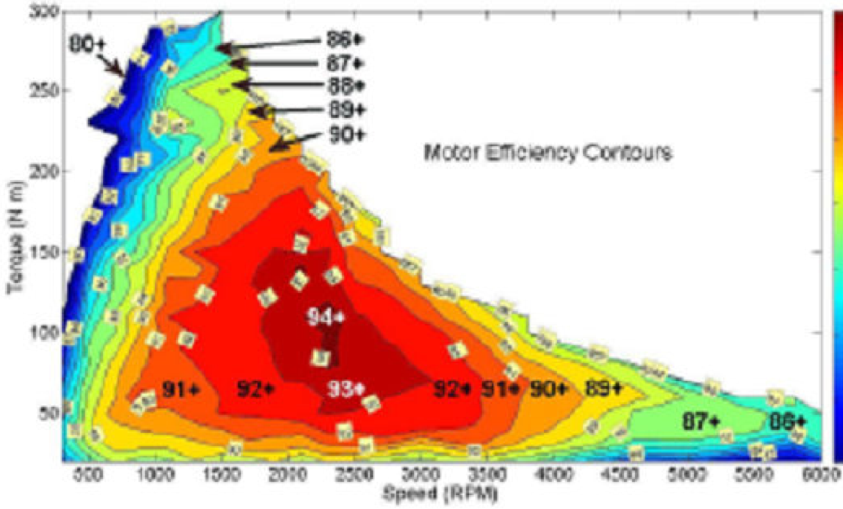

Fig. 3.18. 2004 Prius motor efficiency contour map.

Exhibit 6

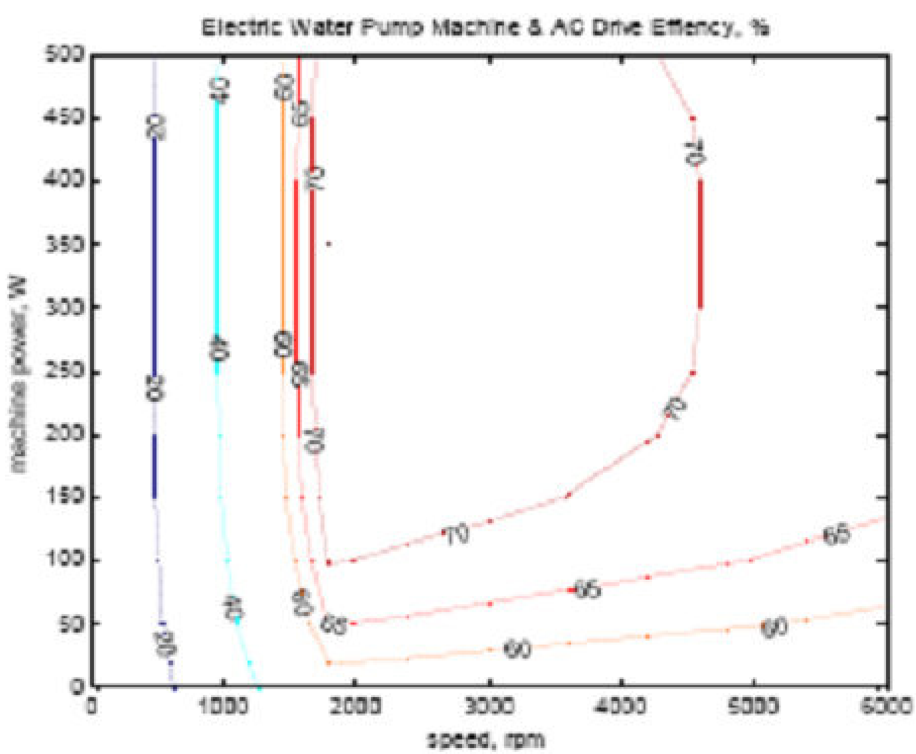

Figure 3-6: Electric Water Pump Machine & Air Conditioning Drive Efficiency

Exhibit 7

Feature	Ricardo Stoichiometric DI Turbo Engine	Mahle Turbocharged, DI Concept Engine SAE 2009-01-1503
Downsizing	57% (for Std Car)	50%
BMEP	25-30 bar	30 bar
Turbo Response	1.5 second time constant	2.5 second time constant (estimated from 4 second total response time)
Turbine Inlet Temperature	950C	1025C
NEDC fuel economy	Not available	25 – 30% better that NA baseline

Exhibit 8

Feature	Ricardo Stoichiometric DI Turbo Engine	Lotus Sabre Engine SAE 2008-01-0138
Downsizing	57% (for Std Car)	32%
BMEP	25 - 30 bar	20.1 bar
Turbine Inlet Temperature	950C	980C 1050C (common) and desired
Fuel RON	87 PON (Pump Octane Number)	95 RON Est 91 PON

Exhibit 9

	FTP	HWFET	US06	Combined	0-60 mph	Displacement	FDR	Rolling R.	Aero	Weight	Eng. Eff	Hybird	Class
Conventional SS													
Base (Baseline)	30.0 -	43.5 -	29.1 -	34.9 -	8.3 -	1.04	3.23	0.00822	0.69	3625	1		Standard Car (Toyota Camry)
Stoich DI Turbo	44.5 48.2%	54.2 246%	32.5 11.7%	48.4 38.7%	8.5	1.04	3.23	0.00822	0.69	3625	1		Standard Car (Toyota Camry)
AT8-2020 to DCT	46.3 4.21%	55.3 1.93%	33.7 3.51%	50.0 3.28%	8.6	1.04	3.23	0.00822	0.69	3625	1		Standard Car (Toyota Camry)
HYBRIDS													
P2 w/Stoich DI Turbo (Rel to Conv SS SCT)	61.6 32.96%	56.3 1.80%	36.6 8.89%	59.1 18.23%	8.6	0.83	3.23	0.00822	0.69	3625	1	24	Standard Car (Toyota Camry)
PS w/Stoich DI Turbo (Rel to Conv SS DCT)	57.5 24.00%	53.3% -3.50%	36.4 8.24%	55.5 11.11%	9.2	0.83	3.23	0.00822	0.69	3625	1	80	Standard Car (Toyota Camry)
PS w/Akins on CPS (Rel to Stoich DI Turbo)	55.1 -4.08%	53.2 -0.18%	38.1 4.61%	54.3 -2.29%	8.5	2.4	3.23	0.00822	0.69	3625	1	80	Standard Car (Toyota Camry)
PS w/Akins on DVA (Rel to Stoich DI Turbo)	58.3 1.5%	54.8 2.7%	38.7 6.1%	56.7 2.1%	8.5	2.4	3.23	0.00822	0.69	3625	1	80	

Exhibit 10

Engines	FTP	HWFET	US06
Baseline	42.1	**62.6**	**37.0**
Stoich_DI_Turbo	46.3	55.3	33.7
Lean_DI_Turbo	48.3	56.4	33.9
EGR_DI_Turbo	48.2	57.6	35.2
Atkinson_CPS	44.5	59.0	35.4
Atkinson_DVA	45.5	57.1	34.5

4. References

Coltman, D., J.W.G. Turner, R. Curtis, D. Blake, B. Holland, R.J. Pearson, A. Arden, and H. Nuglisch, 2008, Project Sabre: A close-spaced direct injection 3-cylinder engine with synergistic technologies to achieve low CO2 output. SAE Paper 2008-01-0138.

Hellenbroich, G., and V. Rosenburg, 2009, FEV's new parallel hybrid transmission with single dry clutch and electric torque support. *Aachener Koolquium Fahrzeug- und Motorentechnik* 2009 18:1209–1222.

Lumsden, G., D. OudeNijeweme, N. Fraser, and H. Blaxill, 2009, Development of a turbocharged direct injection downsizing demonstrator engine. SAE Paper 2009-01-1503.

PQA and Ricardo, 2008, *A Study of potential effectiveness of carbon dioxide reducing vehicle technologies*. Prepared for the U.S. Environmental Protection Agency,

Ricardo, Inc., 2011, *Computer simulation of light-duty vehicle technologies for greenhouse gas emission reduction in the 2020-2025 timeframe*. Prepared for the U.S. Environmental Protection Agency. April 6, 2011.

Staunton, R.H., C.W. Ayers, L.D. Marlino, J.N. Chiasson, T.A., Burress, 2006, *Evaluation of 2004 Toyota Prius hybrid electric drive system*. ORNL technical report TM-2006/423.

Turner, J.W.G., R.J. Pearson, R. Curtis, and B. Holland, 2009, Sabre: A cost-effective engine technology combination for high efficiency, high performance and low CO2 emissions. Low Carbon Vehicles 2009: Institution of Mechanical Engineers (IMechE) conference proceedings.

U.S. Environmental Protection Agency (U.S. EPA), 2006, *Peer Review Handbook, 3rd ed*. Science Policy Council. EPA/100/B-06/002.

Appendix A. Charge to Peer Reviewers

Charge to the Peer Reviewers of Ricardo's "Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe" Report

Charge to Peer Reviewers of "COMPUTER SIMULATION OF LIGHT-DUTY VEHICLE TECHNOLOGIES FOR GREENHOUSE GAS EMISSION REDUCTION IN THE 2020–2025 TIMEFRAME"

As EPA and NHTSA develop programs to reduce greenhouse gas (GHG) emissions and increase fuel economy of light-duty highway vehicles, there is a need to evaluate the effectiveness of technologies necessary to bring about such improvements. Some potential technology paths that manufacturers might pursue to meet future standards may include advanced engines, hybrid electric systems, mass reduction, along with additional road load reductions and accessory improvements.

Ricardo Inc. has developed simulation models including many of these technologies with the inputs, modeling techniques, and results described in the Ricardo Inc. document "COMPUTER SIMULATION OF LIGHT-DUTY VEHICLE TECHNOLOGIES FOR GREENHOUSE GAS EMISSION REDUCTION IN THE 2020–2025 TIMEFRAME"

EPA is seeking the reviewers' expert opinion on the inputs, methodologies, and results described in this document and their applicability in the 2020-2025 timeframe. The Ricardo Inc. report is provided for review. We ask that each reviewer comment on all aspects of the Ricardo Inc. report. Findings of this peer review may be used toward validation and improvement of the report and to inform EPA and NHTSA staff on potential use of the report for predicting the effectiveness of these technologies. No independent data analysis will be required for this review.

Reviewers are asked to orient their comments toward the five (5) general areas listed below. Reviewers are expected to identify additional topics or depart from these general areas as necessary to best apply their particular set of expertise toward review of the report.

(1) Inputs and Parameters. Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Examples might include: engine technology selection, battery SOC swing, accessory load assumptions, etc.) Please comment on any caveats or limitations that these inputs and parameters would affect the final results.

(2) Simulation methodology. Please comment on the validity and applicability of the methodologies used in simulating these technologies with respect to the entire vehicle. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations. Does the model handle synergistic affects of applying various technologies together?

(3) Results. Please comment on the validity and applicability of the results to the light-duty vehicle fleet in the 2020-2025 timeframe. Please comment on any apparent unstated or implicit assumptions that may affect the results, and on any related caveats or limitations.

(4) Completeness. Please comment on whether the report adequately describes the entire process used in the modeling work from input selection to results.

(5) Recommendations. Please comment on the overall adequacy of the report for predicting the effectiveness of these technologies, and on any improvements that might reasonably be adopted by the authors for improvement. Please note that the authors intend the report to be open to the community and transparent in the assumptions made and the methods of simulation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

Comments should be sufficiently clear and detailed to allow readers familiar with the report to thoroughly understand their relevance to the material provided for review. EPA requests that the reviewers not release the peer review materials or their comments until Ricardo Inc. makes its report and supporting documentation public. EPA will notify the reviewers when this occurs.

If a reviewer has questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If a reviewer has any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

Appendix B. Reviewer Resumes

DIONISSIOS (DENNIS) N. ASSANIS

PERSONAL

Degrees

Ph.D., Power and Propulsion, Massachusetts Institute of Technology (M.I.T.), 1985
M.S., Management, Sloan School of Management, M.I.T., 1986
M.S., Mechanical Engineering, M.I.T., 1982
M.S., Naval Architecture and Marine Engineering, M.I.T., 1982
B.Sc., Marine Engineering, Newcastle University, England, 1980

Positions at University of Michigan

Director, Michigan Memorial Phoenix Energy Institute, July 2009-date
Jon R. and Beverly S. Holt Professor of Engineering
Arthur F. Thurnau Professor of the University of Michigan
Chair, Mechanical Engineering, Jan. 2002- Aug. 2007
Professor of Mechanical Engineering, Sept. 1994-date
Professor of Applied Physics, 2003-date
Founding Director for the United States, Clean Vehicle Consortium, U.S.-China Clean Energy Research Center, 2010-2015
Director, Automotive Research Center, Sept. 2000- Oct.2009
Director, W. E. Lay Automotive Laboratory, 1996-date
Fellow, Michigan Memorial Phoenix Energy Institute, 2007-date
Founding Co-Director, General Motors Collaborative Research Laboratory on Engine Systems Research, 2002-2011
Associate Director, General Motors Satellite Research Laboratory, 1998-2002
Deputy Director, Automotive Research Center, Jan. 1996-Aug. 2000
Acting Director, Automotive Research Center, Aug.1995- Dec. 1995
Interim Director, CoE Interdisciplinary Professional Programs, Fall 2001
Founding Director, CoE Automotive Engineering Program, Sept. 1999-Apr. 2002
Founding Director, MEAM Automotive Engineering Program, 1995-1999

Positions at University of Illinois in Urbana-Champaign

Associate Professor of Mechanical Engineering, Aug. 1990 - Aug. 1994
Head, Thermal Sciences/Systems Division II, Aug. 1992 - Aug. 1994
Research Scientist, Office for Supercomputing Applications, Aug. 1991- 1994
Assistant Professor of Mechanical Engineering, Sept. 1985 - Aug. 1990

Positions at Other Institutions

Honorary President, Zhejiang Automotive Engineering Institute, 2009-date
Honorary Professor, Zhejiang Automotive Engineering Institute, 2009-date
Advisory Professor, Shanghai Jiao Tong University, Shanghai, China, 2009-date
Guest Professor, Shanghai Jiao Tong University, Shanghai, China, 2003-2008

Adjunct Research Scientist, Argonne National Laboratory, Energy and Environmental Systems Division, May 1987-2002

Research Assistant, Sloan Automotive Laboratory, Massachusetts Institute of Technology, Sept. 1982- Aug. 1985

Teaching and Research Assistant, Department of Ocean Engineering, Massachusetts Institute of Technology, Sept. 1980-June 1982

Honors and Awards

ASEE Mechanical Engineering Division Ralph Coats Roe Award, 2011

College of Engineering, Stephen S. Atwood Award, 2011

University of Michigan Rackham Distinguished Faculty Achievement Award, 2009

Member, National Academy of Engineering, 2008

ASME, Internal Combustion Engine Award, 2008

ASME Fellow, 2008

Tau Beta Pi Professor of the Year Award, 2006

SAE Award for Research on Automotive Lubricants, 2002

SAE Fellow, 2001

Jon R. and Beverly S. Holt Professor of Engineering, 2000

ASEE Annual Distinguisher Lecturer, College of Engineering, The University of Michigan, April 12, 2000

Teaching Excellence Award, College of Engineering, The University of Michigan, 2000

Arthur F. Thurnau Professor, The University of Michigan, 1999

Excellence in Teaching Award, Mechanical Engineering and Applied Mechanics, The University of Michigan, 1998

ASME Internal Combustion Engine Division Meritorious Service Award, 1997

ASME Internal Combustion Engine Division Speaker Award, 1993,

ASME Internal Combustion Engine Division Speaker Award, 1994

Listed in *Who's Who in America,* 1994-date

Listed in *Who's Who in Science and Engineering,* 1993-date

Listed in *American Men and Women of Science,* 1992-date

University of Illinois Scholar, 1991 - 94

SAE Russell Springer Award, 1991

IBM Research Award, 1991

ASME/Pi Tau Sigma Gold Medal Award, 1990

NSF Presidential Young Investigator Award, 1988-93

Lilly Endowment Teaching Fellow Award, 1988

NSF Engineering Initiation Award, 1987

NASA Certificate of Recognition for Creative Development of a Technical Innovation, 1987

SAE Ralph Teetor Award to Outstanding Young Educators, 1987

Excellent Teacher, listed every semester in student newspaper *The Daily Illini,* 1985-94

Honors, B.Sc. Degree with Distinction, 1980

CONTRIBUTIONS TO ACADEMIC LEADERSHIP AND SERVICE

Contributions as Director, Michigan Memorial Phoenix Energy Institute

As the Director of the Michigan Memorial Phoenix Energy Institute (MMPEI), Professor Assanis leads an organization that manages the development, coordination and promotion of multidisciplinary energy research and education programs across the University of Michigan (UM). MMPEI's mission is to chart pathways to a secure, affordable and sustainable energy future. His current priorities include the following:

- Develop the vision for integrated research thrusts on energy generation, storage, and utilization, and their interconnection with policy, economics, and social impact. Among major efforts, sustainable carbon-neutral transportation has emerged as a powerful research theme for UM that closely couples to the broad sustainability issues and integrated assessments. Electrification of transport, advanced energy storage in batteries and renewable fuels, as well as grid supply and distribution are of crucial importance to maintain UM's status of being a world-leader in automotive and manufacturing engineering. In the area of carbon-neutral electricity, MMPEI is bringing into a common energy systems focus the campus-wide efforts in the areas of nuclear engineering, solar energy, wind, and wave energy. MMPEI is committed to fostering changes that would facilitate the permitting, leasing, construction, and monitoring of renewable energy projects while protecting natural resources.

- Establish new faculty appointments that combine strengths in science/technology with those in public policy, business, economics and social sciences. Examples of multi-disciplinary cluster hires that MMPEI is leading include energy economics, political science and public policy, energy storage, sustainable energy and climate change impacts. These new searches involve multiple Departments from the College of Engineering, the College of Literature, Science and Arts, the Ford School of Public Policy, and the School of Natural Resources and Environment.

- Spearhead the development of innovative and transformative energy literacy across various media including curricular offerings, workshops, lecture series, and seminars. Catalyze cross-disciplinary educational programs in sustainable energy across the UM campus and in collaboration with global partners. Enhance the integration of energy education and research.

- Develop partnerships with other academic institutions, national laboratories, industry, start-ups, venture capitalists, and economic development agencies to promote scientific discovery and its translation to innovation and job creation. As an exemplar, UM is proud to be among the founding members of the Oak Ridge National Lab-led partnership that has won the first, highly competitive DOE energy innovation hub for "Advanced Simulation of Light Water Nuclear Reactors" funded with $122M for five years. MMPEI played a significant role in institutionalizing this strategic partnership which positions UM to attack large-scale problems though the establishment of a discovery innovation network.

- Develop strong international partnerships with first-class peer institutions with the strategic objective of tackling global energy and sustainability problems through education, research, industry transformation and innovative policies. For instance, MMPEI has significantly contributed to the expansion of the UM-Shanghai Jiao Tong University educational collaboration to encompass joint research in renewable energy. With Tsinghua University and other Chinese and US partners in academia, industry and national labs, we have recently won the competition for establishing the highly visible U.S.-China Clean Energy Research Center on Clean Vehicles funded with over $50M for the next five years. With the Fraunhofer Institutes of Germany, we have initiated a landmark international collaboration aimed at the transformation of the transportation industry towards electrical mobility. With the National University of Singapore, UM is proposing the joint development of renewable energy technologies and policies for high-density urban communities that will be demonstrated in Singapore, an ideal test bed for sustainability.

- Under Dr. Assanis' leadership, MMPEI is pursuing a two-pronged approach for the development of comprehensive building facilities for the Institute. First, the UM Regents are funding a $11M renovation and expansion of the Phoenix Memorial Laboratory to provide state-of-the-art space for energy research, as well as the home for MMPEI's administrative and collaborative functions. In parallel, MMPEI is developing a staged plan for the establishment of a multi-disciplinary hub for innovation and entrepreneurship in renewable energy, in partnership with other UM Centers, at the UM North Campus Research Complex.

Contributions as Chair of Mechanical Engineering

As Chair of the Department of Mechanical Engineering (ME) at the University of Michigan (2002-2007), Professor Assanis led the administration and long-range development of the ME Department's academic and research programs. The ME Department is a major academic unit that is educating more than 700 undergraduate students and 500 graduate students (250 Master's and 250 PhDs), and employing 55 tenured and tenure track professorial faculty members, 18 primary research scientists and 70 support staff members in a physical plant of approx. 120,000 square feet spread out over four buildings. Throughout his tenure as ME Chair, the Department's undergraduate and graduate programs were consistently ranked within the top five nationally by U.S. News and World Report. Also, based on data from the 2005-06 academic year, the National Research Council rated the ME graduate program as #4 in the country based on both regression and survey rankings. His efforts have made significant contributions in the following areas:

- Planned strategically to establish and articulate a shared vision for the future that sustains and evolves the ME Department's core academic and research strengths in automotive and manufacturing engineering, while also developing a competitive position into the emerging areas of mechanical engineering, including bio-systems, energy/ eco-systems and micro/nano-systems. As the culmination of these strategic planning efforts, a major addition and remodeling of the ME Building facilities, has emerged as the #2 all-campus building priority for UM's capital outlay plan over the next five years.

- Successfully retained the ME Department's excellent body of faculty and hired outstanding new faculty (11 new Professors and 15 Research Scientists). Promoted in rank 27 faculty members, including 5 women faculty who reached the rank of Professor. In addition to assessing and rewarding the performance of professorial faculty, implemented procedures for the annual review and merit raises of primary research faculty. Mentored junior faculty members in their professional careers and made a deliberate effort to address issues that could compromise their success. Nominated a number of colleagues, students, alumni and staff who received prestigious professional awards, both outside and within the University, including four new endowed chairs.

- Enhanced the ME Department's efforts to create a multi-cultural and diverse intellectual environment by retaining all women and underrepresented minority (URM) faculty; by hiring thee more women faculty members for a total of 10 (18% of ME faculty); by strategically recruiting URM and women students through K-12 programs, the Detroit Area Pre-College Engineering Program, and the NSF Research Experience for Undergraduates Program; and by supporting mentorship groups including Unified Minority Mechanical Engineers and Society of Women Engineers. Improved communications among the students, alumni, faculty and staff.

- Oversaw financial planning, budgets and expenditures for the ME Department (annual budget of approx. $14M in general funds and more than $28M in research funds and gifts) and introduced "paperless" electronic tools in the areas of student services, financial reporting, and faculty recruiting. Participated in fundraising and pubic relations efforts for the ME Department and College of Engineering in close coordination with the development staff. Through these efforts, new endowed professorships, a number of undergraduate student scholarships, and new graduate fellowships from industry, and a prestigious named lectureship series about the role of the *Engineer in Society* have been attracted to the ME Department.

- Made significant progress towards a "paperless" administration through the development and implementation of electronic solutions in the areas of student services (with web-based graduate application and admissions tracking systems), financial reporting (with accounting statements for contracts on line), faculty recruiting and faculty data center.

- Promoted the systematic exchange of faculty and students with strategically selected global partners, notably with the Shanghai Jiao Tong University, the Korean Advanced Institute for Science and Technology, Seoul National University and the Technical University of Berlin.

- Enhanced the strong tradition of an active and engaged External Advisory Board (EAB) which has served as a model for other CoE Departments and the University of Michigan's Transportation Research Institute (UMTRI).

- Promoted the development of K-12 programs intended to spark the interest of the brightest youngsters – including women and traditionally underrepresented groups in math, science and engineering.

Contributions as Director of Automotive Engineering Program

As the Founding Director of the Master's of Engineering Program in Automotive Engineering (AUTO), I was responsible for designing the curriculum and launching the new degree Program, first in the Department of Mechanical Engineering and subsequently as a College-wide program in the College of Engineering. My responsibilities have included recruiting prospective students, advising all M. Eng. students, developing new courses, and pursuing international collaborations for joint degree offerings with global Universities, and especially Aachen (Germany) and Loughborough (UK) as part of the Ford Global Automotive Systems Master's degree. As part of our curriculum improvement activities, I founded the College of Engineering AUTO Council and led its efforts to develop and evolve a strong academic curriculum that meets industry needs. I also worked very effectively with the UM Center for Professional Development to offer to industry a distance-learning version of our M.Eng. Program. Our visionary pursuit of distance learning teaching has set a standard for other programs to emulate.

Overall, I strived to grow our AUTO program, while simultaneously improving the quality of the entering students and courses offered. Our goals were met with great success, as evidenced by the enrollment in the AUTO program, which exceeded 100 students within 5 years from the program's introduction, and the excellent job placement and very positive feedback expressed by many of our continuing students and graduates.

Contributions as Interim Director of Interdisciplinary Professional Programs

As the Interim Director of the College of Engineering's Interdisciplinary Professional Programs (INTERPRO), I provided stability and leadership during a period of transition and growth to six interdisciplinary programs, automotive engineering, financial engineering, integrated micro-systems, manufacturing engineering, pharmaceutical engineering, and plastics engineering. During my tenure as Director and working with the INTERPRO Directors' Council, I oversaw the management of the large growth in student enrollment which reached an all time high (320 enrolled students) in the history of the INTERPRO programs. Most of this growth was accounted by part-time, distance learning professionals. I stepped down from my role as INTERPRO Director and AUTO Program Director to assume the position of Chair of Mechanical Engineering.

OTHER CONTRIBUTIONS TO SERVICE

Major Committee Assignments at University of Michigan

University of Michigan Committees:

Vice President of Research Committee on Entrepreneurship, 2011
Vice President of Research Director's Council, 2009-date
North Campus Research Complex, Director's Committee, 2009-2010
Rackham Distinguished Faculty Achievement Award Committee, 2009-2011
Panel on Engagement/Institutes, Site Visit of High Learning Commission on University Re-Accreditation, March 2010
UM Energy Council, Founding Member, 2003-2007

Charter member of the team that actively pursued the development of a UM research thrust on Energy working in partnership with other Colleges, articulated the vision statement for the thrust, and recommended to the UM administration the development of a University-wide Energy Laboratory at the site of the decommissioned nuclear reactor.

President's Committee on Intellectual Property Policy, 2001-02, Member
University Senate, 1995-98, Elected Senator

College of Engineering Committees:

College of Engineering (COE) Budget Task Team, 2005-07, Member
COE Center of Professional Development Executive Committee, 2005-06, Member
COE Faculty Fellows Program, October 11-12, 2002, Panelist
COE Interdisciplinary Professional Program Directors Committee, 2001, Chair
COE Nominating Committee, 2000-2001, Chair
COE Automotive Council, 1999-date, Chair
COE Curriculum Committee, 2000, Member
COE Committee on Reshaping Graduate Education at the Master's Level, 1998-99, Member
COE Committee on M. Eng. Programs, 1998-99, Member
COE UM-National University of Singapore Committee on Establishment of

Joint M.Eng. Program in Automotive Engineering, 1997-98, Chair
COE Committee on Faculty Incentives for Continuing Education (ICE) and
Distance Learning Instruction, 1997-98, Member

Departmental Committees:
ME Honors and Awards Committee, 2008-2011
ME (formerly MEAM) Advisory Committee,
Elected Member 1995-96, 1997-98 and Fall 2001
Chair, 2002-2008
ME (formerly MEAM) Planning Committee
Member, 1997-98
Chair, 2002-2008
MEAM Thermal Science Instructional Area Coordinator, 1997-2000
MEAM Space Task Force Committee, 1996-98, Member
W. E. Lay Automotive Laboratory Test Cell Committee, 1994-present, Chair
W. E. Lay Automotive Laboratory Renovations Committee, 1994-95, Member
MEAM Laboratory and Safety Committee, 1995-1998, Member

Service to Other Organizations

1. External Boards

Member, Board of Directors, NextEnergy, a non-profit organization with a mission to be one of the nation's leading non-profit research catalysts and business accelerators for alternative and renewable energy, 2010-date.

Member, Board of Directors, Consortium for Advanced Simulation of Nuclear Reactors, an energy innovation hub led by Oak Ridge National Laboratory (ORNL) and funded by DOE up to $122 million, 2010-2015.

Member, President's Council of Advisors on Science and Technology (PCAST) Working Group on Energy Technology Innovation System, 2010.

Co-Chair, National Academy of Engineering Annual German-American Frontiers of Engineering GAFOE Symposium, 2010-2012.

Member, Science and Technology Council Advisory Board, Cummins Engine Company, Inc., Columbus, IN, 2010.

Member, International Advisory Board, Center for Clean Combustion Energy, Tsinghua University, China, 2010-2013.

Chair, Advisory Board, Tula Technology, Santa Clara, CA, 2009-date.

Member, State of Michigan Great Lakes Wind Council, 2009-2010.

Member, Energy Council of the CTO Forum, a Silicon Valley-based organization that brings together Chief Technology Officers from a cross-section of businesses and industries to discuss critical issues at the intersection of technology, energy and the environment, 2009-date.

Member, External Advisory Board, Center for Mobile Propulsion, RWTH Aachen University, 2009-date.

Member, National Academy of Sciences Committee on Fuel Economy of Medium- and Heavy-Duty Vehicles, appointed by the National Research Council's Board on Energy and Environmental Systems, 11/08-5/31/10.

Member, ASME Internal Combustion Engine Division Executive Committee, 2008-10.

Chair, King Abdullah University of Science and Technology (KAUST) Search for Director of Center for Clean Combustion Energy, 2008-09.

Member, External Validation Panel for Launching MSc degree in Automotive Engineering Design, Hong Kong Polytechnic University, 2007.

Member, Global External Advisory Board, Department of Mechanical Engineering, Korean Advanced Institute for Science and Technology (KAIST), 2006-2008.

Member, External Advisory Board, Department of Mechanical Engineering, Georgia Tech, 2004-date.

Member, External Advisory Panel, "Business Briefing: Global Automotive and Manufacturing and Technology," World Market Research Centre, May 2002.

2. Editorships

Editor, *International Journal of Automotive Technology,* 2008-2011

Editorial Board, *International Journal of Powertrains*, 2010-date

Editorial Board, *International Journal of Engine Research*, 2003-2012

Editorial Board, *International Journal of Automotive Technology,* 2005-2008

Associate Editor, *ASME Journal for Gas Turbines and Power*, 1996-2007

Scientific Board, *Ingineria Automobilului,* 2007-date

Guest Editor, *International Journal of Heavy Vehicle Systems*, 2004

3. Professional Society Memberships

American Society of Mechanical Engineers, Fellow
    Executive Committee Member, ICE Division, 2008-2013
    Journal Associate Editor, 1996-2008
    Past Chair of Student Activities, ICE Division
Society of Automotive Engineers, Fellow
    Member, SAE Research Executive Committee, 2000-date
    Faculty Advisor, University of Michigan, 1996-2004
    CoE Future Car, Faculty Co-Advisor, 1997-98
    Member, Advanced Powerplant Committee
    Member, Passenger Car Readers Committee
    Member, Vehicular Heat Exchanger and Heat Transfer Committee
American Society for Engineering Education, Member
Sigma Xi, Member
New York Academy of Sciences, Member
The Combustion Institute, Member
Society of Naval Architects and Marine Engineers, Associate Member

4. Organizing and Chairing Conferences, Sessions, Workshops, Lectures

Co-Chair and Co-Organizer, Michigan Memorial Phoenix Energy Institute and Fraunhofer Institutes of Germany Joint Conference, "Towards Carbon Neutral Vehicles," Plymouth, MI, October 21, 2010.

Moderator, Panel on "Fuel Economy and Clean Transportation of the Future," Michigan Memorial Phoenix Energy Institute and Fraunhofer Institutes of Germany Joint Conference, "Towards Carbon Neutral Vehicles," Plymouth, MI, October 21, 2010.

Chair, Plenary Session on "Future Mobility - Energy, Environment & Carbon Management," Emissions 2010, Michigan League, University of Michigan, Ann Arbor, June 15-16, 2010.

Co-Organizer and Co-Chair, 11th International Conference on Present and Future Engines for Automobiles, Shanghai, China, May 30-June 3, 2010.

Organizer, 3rd Annual Michael E. Korybalski Endowed Lecture in Mechanical Engineering: "Engineering, Innovation and the Challenges of the 21st Century," given by Charles Vest, President NAE and Emeritus President, M.I.T., May 12, 2010

Co-Chair, National Academy of Engineering Annual German-American Frontiers of Engineering GAFOE Symposium, Oak Ridge National Laboratory, Oak Ridge, TN, April 22-25, 2010.

Chair and Co-Organizer, ARC Annual Conference, "Critical Technologies for Modeling and Simulation of Ground Vehicles," May 12-13, 2009

Organizer, 2nd Annual Michael E. Korybalski Endowed Lecture in Mechanical Engineering: "Size Matters," given by Dr. Roger McCarthy, Emeritus Chairman and CEO, Exponent, Inc., May 4, 2009

Chair, Prime Power, National Defense Industrial Association – Michigan Chapter, Power and Energy Workshop, Troy, MI, November 18-19, 2008

Chair and Co-Organizer, ARC Annual Conference, "Critical Technologies for Modeling and Simulation of Ground Vehicles," May, 2008

Member of Scientific Committee, International Workshop on Advances in Combustion Science and Technology, India Institute of Technology, Kanpur, India, Dec. 31, 2007- Jan. 8, 2008

Organizer, Inaugural Michael E. Korybalski Endowed Lecture in Mechanical Engineering: “Driving to a Sustainable Future, a New DNA for the Automobile,” given by Dr. Lawrence Burns, VP Research, Development and Planning, General Motors

Chair and Co-Organizer, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May, 2007.

Member of Scientific Committee, 2nd International Symposium on Clean and Efficient Combustion Engines, Tianjin, China, July 10-13, 2006.

Chair and Co-Organizer, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May, 2006.

Chair and Co-Organizer, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May, 2005.

Chair and Co-Organizer, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May, 2004.

Co-Organizer, “Premixed Charge Compression Ignition Engines,” 2003 JSAE/SAE International Spring Meeting, Yokohama, Japan, May 19-22, 2003.

Chair and Co-Organizer, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May, 2003.

Co-Organizer and Chair, “Homogeneous Charge Compression Ignition Engines,” 2003 SAE World Congress, Detroit, MI, March 3-6, 2003.

Chair and Co-Organizer, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May, 2002.

Organizer, “Homogeneous Charge Compression Ignition Engines,” 2002 SAE International Spring Fuels & Lubricants Meeting, Reno, Nevada, May 6 - 8, 2002.

Co-Organizer, “Advanced Hybrid Powertrain Systems,” 2002 World Congress, Detroit, MI, March 4-7, 2002.

Co-Organizer, “Homogeneous Charge Compression Ignition Engines,” 2002 World Congress, Detroit, MI, March 4-7, 2002.

Co-Organizer and Chair, “Homogeneous Charge Compression Ignition Engines,” ASME Fall Technical Conference, Argonne, IL, Sep. 23-26, 2001.

Co-Organizer, “Homogeneous Charge Compression Ignition Engines,” SAE 2001 Fall Fuels and Lubricants International Conference, San Antonio, TX, September 24-27, 2001.

Member, Advisory Committee, COMODIA 2001, *International Symposium on Diagnostics and Modeling of Combustion in Internal Combustion Engines*, Nagoya, Japan, July 1-4, 2001.

Organizer and Chair, “Homogeneous Charge Compression Ignition Engines,” SAE 2001 Spring Fuels and Lubricants International Conference, Orlando, Florida, May 7-9, 2001.

Chair and Co-Organizer, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May 15-16, 2001.

Co-Organizer and Co-Chair, “Hybrid Electric Vehicles,” SAE International Congress and Exhibition, March 5-8, 2001.

Co-Organizer and Chair, “Novel SI and CI Combustion Systems,” SAE 2000 Fuels and Lubricants International Conference, Paris, France, June 19-22, 2000.

Co-Organizer and Session Chair, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May 2000.

Co-Organizer, “Direct Injection Engines and Sprays,” ASME-ICE Sprint Technical Conference, San Antonio, TX, April 9-12, 2000.

Co-Organizer, “Homogeneous Charge Compression Ignition Engines,” SAE International Fuel and Lubricants Meeting, Toronto, Canada, Oct. 25-28, 1999.

Organizer, “Modeling and Simulation of Direct Injection Engine Processes,” ASME-ICE Fall Technical Conference, Ann Arbor, MI, Oct. 16-20, 1999.

Host, ASME-ICE Fall Technical Conference, Ann Arbor, MI, Oct. 16-20, 1999.

Member of Technical Program Committee, Vehicle Thermal Management Systems VTMS-4 International Conference, London, UK, May 24-26, 1999.

Co-Organizer and Session Chair, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May 1999.

Organizer, “Modeling and Simulation of Engine Combustion Processes,” ASME-ICE Spring Technical Conference, Columbus, IN, April 24-28, 1999.

Organizer, “Advanced Diesel Engine Powertrains,” SAE International Congress and Exposition, Detroit, MI, Feb. 23-26, 1999.

Organizer, “Modeling and Simulation of Engine Combustion Processes,” ASME-ICE Fall Technical Conference, Clymer, New York, September 27-30, 1998.

Moderator, “The Future of Automotive Systems,” SAE Automotive Systems Testing Topical Technical Symposium (TOPTEC), Novi, MI, October 14-15, 1998.

Co-Organizer and Session Chair, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May 1998.

Chair, Panel on Surface Engineering and Tribology, SAE International Congress and Exposition, Detroit, MI, Feb. 23-26, 1998.

Organizer, “Adiabatic and Miller Cycle Engines,” SAE International Congress and Exposition, Detroit, MI, Feb. 23-26, 1998.

Organizer, “New Analytical Methods in Engine Design,” ASME-ICE Fall Technical Conference, Madison, WI, Sept. 27 - Oct. 1, 1997.

Co-Organizer and Session Chair of ARC Annual Conference, “Critical Technologies in Modeling and Simulation of Ground Vehicles,” June 3-4, 1997.

Member of Technical Program Committee, Vehicle Thermal Management Systems VTMS-3 International Conference, Indianapolis, IN, May 19-22, 1997.

Organizer, “New Analytical Methods in Engine Design,” ASME-ICE Spring Technical Conference, Fort Collins, Colorado, April 27-30, 1997.

Co-Organizer, "Adiabatic Engines", SAE International Congress and Exposition, Detroit, MI, 1997.

Member, Program Review Subcommittee, Twenty-Sixth International Symposium on Combustion, Naples, Italy, July 28-Aug. 2, 1996.

Co-Organizer and Session Chair, ARC Annual Conference, “Critical Technologies for Modeling and Simulation of Ground Vehicles,” May 29-30, 1996.

Organizer, Student Paper Competition, ASME ICE Fall Technical Conference, Fairborn, OH, Oct. 20-23, 1996.

Co-Organizer and Chairman, “Engine Simulations,” ASME ICE Fall Technical Conference, Fairborn, OH, Oct. 20-23, 1996.

Co-Organizer, “Adiabatic Engines,” SAE International Congress and Exposition, Detroit, MI, 1996.

Organizing Committee, Fraunhofer Institute-University of Michigan Joint Conference, “The Best of German/American Automotive Technology,” Southfield, MI, June 27-28, 1995

Co-Organizer and Chairman, “Engine Simulations,” ASME Engine Technology Spring Conference, Marietta, Ohio, April 23-26, 1995.

Co-Organizer and Session Chair of ARC Annual Conference, “Critical Technologies in Modeling and Simulation of Ground Vehicles,” April 19-20, 1995

Co-Organizer, “Adiabatic Engines,” SAE International Congress and Exposition, Detroit, MI, 1995.

Chairman and Co-Organizer, “Modeling Engine Processes,” ASME Fall Technical Conference, Lafayette, IN, 1994.
Chairman and Co-Organizer, “Adiabatic Engines,” SAE International Congress and Exposition, Detroit, MI, 1994.
Chairman and Organizer, “Engine Design,” Energy Technology Conference and Exhibition, New Orleans, LA, 1994.
Chairman and Co-Organizer, "Engine Simulation and Controls," ASME Fall Technical Conference, Morgantown, WV, 1993.
Co-Chairman, "Engine Sprays," ILASS, Worcester, MA, 1993.
Chairman, “Vehicle Cooling Systems,” International Conference on Vehicle Thermal Management Systems, Columbus, OH, 1993.
Chairman and Co-Organizer, “Adiabatic Engines,” SAE International Congress and Exposition, Detroit, MI, 1993.
Vice-Chairman and Co-Organizer, “Intake Air Management,” Energy Technology Conference and Exhibition, Houston, TX, 1993.
Chairman and Co-Organizer, “Adiabatic Engine Components,” Vice-Chairman, “High Temperature Engine Heat Transfer,” SAE International Congress and Exposition, Detroit, MI, 1992.
Vice-Chairman and Co-Organizer, “Engine Simulation,” Energy Technology Conference and Exhibition, Houston, TX, 1992.
Co-Organizer, “Panel on Post-95 Low Emission Engines,” ASME Energy Technology Conference and Exhibition, Houston, TX, 1991.
Moderator and Co-Organizer, “Panel on Post-95 Low Emission Engines,” SAE International Congress and Exposition, Detroit, MI, 1991.
Chairman and Co-Organizer, “Adiabatic Engine Components,” Vice-Chairman, "High Temperature Engine Heat Transfer," SAE International Congress and Exposition, Detroit, MI, 1991.
Chairman and Co-Organizer, “Adiabatic Engine Components,” Vice-Chairman, "High Temperature Engine Operation," SAE International Congress and Exposition, Detroit, MI, 1990.
Vice-Chairman, “Basic Engine Processes,” Energy Technology Conference and Exhibition, Houston, TX, 1989.
Chairman and Co-Organizer, “Adiabatic Engine Components,” Vice-Chairman, "High Temperature Tribology," SAE International Congress and Exposition, Detroit, MI, 1989.
Vice-Chairman and Co-Organizer, “International Symposium on Flows in Reciprocating Internal Combustion Engines,” ASME Winter Annual Meeting, Chicago, IL, 1988.
Vice-Chairman, “Basic Engine Processes,” American Society of Mechanical Engineers, Energy Technology Conference and Exhibition, New Orleans, LA, 1988.
Assistant Chairperson, “High Temperature Tribology,” SAE International Congress and Exposition, Detroit, MI, 1988.
Chairman, “Engine Simulation Studies,” International Association for Vehicle Design Fourth International Congress, Genera, Switzerland, 1987.
Assistant Chairperson, “Adiabatic Engines,” SAE International Congress and Exposition, Detroit, MI, 1987.

5. Service as Consultant to Government and Industry

Assanis and Associates, Inc., President, Ann Arbor, MI (2000-date)
Optimetrics, Inc., Ann Arbor, MI (1999)

Textron Automotive, Southfield, MI (1998)
M.A.N.A.G.E., Inc., President, Ann Arbor, MI (1995-1998)
Automated Analysis Corporation, Ann Arbor, MI (1996)
Mobil Technology Company, New Jersey (1996-1997)
GM Electromotive Division, La Grange, IL (1988-1992)
National Aeronautics and Space Administration, Cleveland, OH (1988)
Adiabatics, Inc., Columbus, IN (1986-1991)
Science Application International Corp., Seattle, WA (1986-1987)

CONTRIBUTIONS TO EDUCATION

Sustained Commitment to Education

I have sustained my passionate commitment to education for over 20 years. As an Assistant and Associate Professor at the University of Illinois at Urbana-Champaign, I have taught a range of thermal science courses with student evaluations of my teaching consistently placing me at the very top in a group of 50 faculty members. After joining the University of Michigan, my teaching evaluations (4.74/5.0 average for the quality of the courses I have taught and 4.85/5.0 for the effectiveness of my teaching) have continued to be among the highest in the Mechanical Engineering Department (55 tenured or tenure track faculty) and the College of Engineering (more than 320 faculty members).

In 1987, I was honored with the Society of Automotive Engineers Ralph Teetor Award, given to 20 outstanding engineering educators nationwide each year. In 1988, I was one of six young UIUC faculty members selected in campus-wide competition to receive Lilly Teaching Fellow Awards. In 1990, I received the American Society of Mechanical Engineers/Pi Tau Sigma Gold Medal Award given annually in nationwide competition to the best mechanical engineer 10 years after graduation. In 1991-94, I was named University of Illinois Scholar for my contributions to research and teaching. I am truly gratified to have been honored with the 1997-98 MEAM Excellence in Teaching Award, the 2000 College of Engineering Teaching Excellence Award, the distinguished Arthur F. Thurnau Chaired Professorship, and as the inaugural recipient of the Jon R. and Beverly S. Holt Chaired Professorship.

Teaching Philosophy

I have always felt that a successful educator must love teaching and be able to convey excitement for learning to his/her students. Many of my activities as a teacher and mentor are governed by my strong belief that the key to effective teaching is to be enthusiastic about your teaching and to genuinely care about passing your knowledge to your students. I personally strive to show my students my own excitement about the material and to motivate them to make a sincere effort to master the subject. I have always emphasized the importance of an engaging and interactive teaching-learning process, and created an open and informal atmosphere in the class that encourages students to ask or answer questions. I have taken some bold steps to shift the paradigms of teaching theoretical concepts to engineers, infused my own scholarly activities into the classroom and shared my teaching techniques with my colleagues and future educators. I have stressed my belief that the only way to learn a subject is through hard work and application of your knowledge to real projects, and repeatedly found that students will work hard as long as they are motivated, encouraged when they face adversity and rewarded for their intellectual accomplishments.

Beyond the traditional classroom teaching, I have adopted a holistic approach to the teaching/learning process and utilized effectively the time outside the classroom to advise, mentor, coach and teach the students. I have advised more than 50 doctoral, 100 Master's and M.Eng. students and hundreds of undergraduate students. I believe that sound advice and broadening of their perspective can have a critical impact in the students' future careers. I am gratified that several of my students have emulated me as a role model and have joined academia, including (within the past five years) Clemson University, The Cooper Union for the Advancement of Science and Art, Kansas University, Texas A&M University, United States Merchant Marine Academy and the University of Michigan. I have also greatly enjoyed being the Faculty Advisor of the student chapters of the Society of Automotive Engineers and the American Society of Mechanical Engineers, working with the various student project teams, helping them in their fundraising efforts, and addressing their technical and administrative needs. Getting to know the undergraduate students better and contributing to their education outside the classroom through special projects is time consuming, but can be extremely rewarding to both the students and the teacher.

Teaching Innovations

I am particularly proud of the new perspective I have brought to the student teaching and learning process. The traditional way of teaching undergraduate courses in thermo-sciences and their applications to energy conversion and internal combustion engines has been through lectures and the use of highly idealized models. These ideal models inherently make crude assumptions so that results are often far from reality. Without compromising teaching of the fundamentals, I have introduced an innovative approach to further the education of my students through the incorporation and coordinated use of a series of hands-on laboratories, computer simulation tools, scientific movies, and real life case studies that are presented within and in parallel with the lectures. Sophisticated laboratory experiments and realistic simulation programs provide a more complete understanding of the important physical processes. Students can use the simulation models to compare and analyze their experimental data under similar operating conditions, and suggest ways to improve either the simulation models or the experimental techniques.

In my continuing efforts to enrich the class content, I have also relied on the use of the internet and distance learning. With my graduate student instructors, we have developed integrated learning environments that can be used asynchronously, and at the student's learning pace, to bring together lecture notes, the blackboard, assignments, solutions, clipboards, laboratory demos, simulation runs and engine movies in digital media. We are now planning to run laboratory experiments live from the classroom, or for that matter from any internet connection, to enable students to appreciate lecture content and theory in the light of reality with live demonstrations. Through these innovative approaches, I constantly strive to add another dimension to the student learning.

Infusion of Scholarly Contributions into Teaching-Learning Process

My teaching interests parallel and complement my research interests, as my philosophy is that an excellent teacher must be at the same time a leader in his field of research. Only this way I feel I can give my students the best and most relevant education to enable them become leaders in their fields. In the course of my group's research activities, we have developed a large body of engine simulation software that is extensively used by automotive manufacturers in engine development. With the ever-increasing capabilities of personal computers and graphical programming languages such as C++ and MATLAB-SIMULINK, it has become possible to infuse user-friendly, student versions of these computer simulations to the classroom, thus greatly contributing to my effective teaching. My research activities have also enabled me to rejuvenate the Walter Lay Automotive Laboratory, thus contributing advanced engine experiments to our classes and exposing our students to state-of-the-art laboratory set-ups (http://me.engin.umich.edu/autolab/). These activities have contributed to reaffirming U of M's leadership in automotive engineering.

Contributions to New Course Development

Although the University of Michigan has had a long tradition of excellence in the instruction of internal combustion engines, when I started my career as a Professor at Michigan I realized that our engine-related courses and research facilities were not adequate to meet the current demands of the industrial and research communities for automotive engineers. In order to give our students the best possible education in the field, I have taken a series of steps. First, I completely revised the lectures of our undergraduate/beginner graduate course (ME 438) in internal combustion engines. In addition, I developed and incorporated a series of laboratories as part of the course, which was thus converted from three to four credit hours. This course enrollment has almost doubled in size following my revisions, and has been offered simultaneously via distance learning to industry. Second, based on my scholarly activities, I developed a graduate level course (originally ME 534 and now renumbered as ME538) that deals with the application of thermal sciences to the simulation and design of modern combustion engines. Third, I have developed with my undergraduate and graduate students a single-cylinder engine laboratory experiment that has been used as part of our thermal science laboratory class.

As part of my activities as the Director of the Automotive Program, I oversaw the development of the curriculum for the new degree program and contributed a number of the new modules that were essential to achieving the goals M.Eng. program. In order to broaden the horizons of automotive engineers, I introduced a two semester sequence of automotive seminars (ME 591 and ME 592, now renumbered as ME 501), delivered by industry leaders, that exposed the students to the wide spectrum of interdisciplinary engineering activities involved in the process of development, design, and manufacturing of complex automotive systems. In one of its offerings, the UM automotive seminar class was focused on Vehicle Energy, in global collaboration with Aachen University, Germany, and Ford Motor Company. Furthermore, to provide our automotive engineering students with practical experience in team building, carrying out projects in interdisciplinary teams, and in developing and managing projects, I introduced the capstone M.Eng. Automotive project (ME 593, now renumbered as ME 502). The Automotive Seminars and Project experiences we provide our students have been a model for similar "practimum" programs introduced by several Departments in the College of Engineering.

As part of my activities as the Director of the Michigan Memorial Phoenix Energy Institute, I have co-developed and moderated a graduate level interdisciplinary seminar on "The Power of *And*: Energy Systems and Policy Opportunities for the U.S." The objective of the seminar series is to introduce the audience to the power of integrated energy systems and the promise it holds to craft an energy policy for the United States that ensures plentiful and low-cost energy, national security and sustainable economic growth. The seminar series draws on the collective knowledge and experience of U-M faculty, staff and students.

Courses Taught at University of Michigan

Date	Course	Course Title	Enroll	Crs Eval	Instr Eval
Winter 95	ME 534	Advanced Internal Combustion Eng.	23	4.45	4.54
Fall 95	ME 438	Internal Combustion Engines	42	4.85	4.85
Winter 96	ME 534	Advanced Internal Combustion Eng.	21	4.87	4.97
Winter 96	ME 592	Automotive Eng. Seminar II	8	n/a [1]	n/a
Fall 96	ME 438	Internal Combustion Engines	69 (43+26)[2]	4.83	4.85
Fall 96	ME 591	Automotive Eng. Seminar I	18	n/a	N/A
Winter 97	ME 534	Advanced Internal Combustion Eng.	18	4.86	4.94
Winter 97	ME 592	Automotive Eng. Seminar II		n/a	n/a
Fall 97	ME 438	Internal Combustion Engines	68 (37+31)	4.80	4.88
Fall 97	ME 591	Automotive Eng. Seminar I	12	n/a	n/a
Winter 98	ME 534	Advanced Internal Combustion Eng.	32	4.17	4.72
Winter 98	ME 592	Automotive Eng. Seminar II	40 (15+25)	n/a	n/a
Fall 98	ME 438	Internal Combustion Engines	50	4.86	4.94
Fall 98	ME 591	Automotive Eng. Seminar I		n/a	n/a
Winter 99	ME 592	Automotive Eng. Seminar II		n/a	n/a
Fall 99	ME 438	Internal Combustion Engines	88 (53+35)	4.83	4.95
Fall 99	ME 591	Automotive Eng. Seminar I	33 (18+15)	n/a	n/a
Winter 00	ME 534	Advanced Internal Combustion Eng.	23	4.71	4.85
Winter 00	ME 592	Automotive Eng. Seminar II (Vehicle Energy Seminar)	38 (23+15)	n/a	n/a
Fall 00	ME 591	Automotive Eng. Seminar I	33 (18+15)	n/a	n/a
Fall 01	ME 438	Internal Combustion Engines	66 (41+25)	4.85	4.90
Fall 01	ME 591	Automotive Eng. Seminar I	40 (15+25)	n/a	n/a
Fall 02	ME 438	Internal Combustion Engines	53	4.85	4.85
Fall 03	ME 438	Internal Combustion Engines	72 (32+40)	4.97	4.97
Fall 04	ME 438	Internal Combustion Engines	54	4.91	4.93
Fall 05	ME 438	Internal Combustion Engines	70 (50+20)	4.88	4.88
Fall 06	ME 438	Internal Combustion Engines	50	4.92	4.91
Winter 08	ME 599	Analysis and Control of Alternative Powertrains	26 (20+6)	4.42	4.22
Fall 08	ME 438	Internal Combustion Engines	40	4.94	4.94
Wint 09	ME 538	Advanced ICEs	32	4.54	4.80

[1] Organizer and host of Automotive Engineering Seminar Series I and II. Standard course evaluation forms not applicable (n/a).
[2] Distribution designates student enrollment for on-campus and distance learning students.

Offerings of Short Courses and Workshops

I am a proponent of life-long learning and have frequently taught short courses and workshops to practicing engineers in industry. Examples are:

"Modeling and Computer Simulation of Internal Combustion Engines," Chair, Continuing Engineering Education, University of Michigan, September 9-13, 1996; July 7-11, 1997; June 29-July 3, 1998; July 5-9, 1999; July 10-14, 2000.

"Basic Engines and Their Controls," Chair, Continuing Engineering Education, Motorola, Deerfield, IL, two-day offerings, 1996-2005.

One-on-One Student Instruction and Mentorship

Post-Doctoral Fellows Mentored

1. George Papageorgakis (now with ExxonMobil)
2. Dohoy Jung (now Assistant Professor at UM-Dearborn)
3. George Delagrammatikas (now Assistant Professor at Cooper Union)
4. Sang-Jin Hong (now with Ford Motor)
5. Chris Depcik (now Assistant Professor at University of Kansas)
6. Timothy Jacobs (now Assistant Professor at Texas A&M)
7. Christos Chryssakis (now Research Scientist at NTU, Athens)
8. Vassilis Hamosfakidis (now with Risk Metrics)
9. Andreas Malikopoulos (now at ORNL)
10. Robert Prucka (now Assistant Professor at Clemson University)
11. Chaitanya Sampara (now at NanoStellar)
12. Andrew Ickes (now at Argonne National Laboratories)
13. Hee Jun Park (now at Samsung Heavy Industries, Korea)
14. Seung Hwan Keum (continuing in my group)
15. Byungchan Lee (now at UM- Dearborn)
16. Will Northrop (now at GM R&D)
17. Michael Smith (now at University of Michigan)

Ph. D. Committees Chaired at University of Michigan

1. Xiaobo Sun, 1996, Chair
2. George Papageorgakis, 1997, Chair
3. Apoorva Agarwal, 1998, Chair
4. Dohoy Jung, 2000, Chair
5. George Delagrammatikas, 2001, Co-Chair (with P. Papalambros)
6. Sang-Jin Hong, 2001, Co-Chair (with M. Wooldridge)
7. Scott Fiveland, 2001, Chair
8. Stani Bohac, 2002, Chair
9. Kukwon Cho, 2003, Co-Chair (with Z. Filipi)

10. Guntram Lechner, 2003, Chair
11. Christopher Depcik, 2003, Chair
12. Bruno Vanzieleghem, 2004, Co-Chair (with H. Im)
13. Pin Zeng, 2004, Chair
14. Wooheum Cho, 2004, Chair
15. Junseok Chung, 2004, Co-Chair (with Z. Filipi)
16. Tim Jacobs, 2005, Chair
17. Aris Babajimopoulos, 2005, Chair
18. Ron Grover, 2005, Chair
19. Christos Chryssakis, 2005, Chair
20. Bin Wu, 2005, Co-Chair (with Z. Filipi)
21. Sangseok Yu, 2006, Co-Chair (with D. Jung)
22. Vassilis Hamosfakidis, 2006 (Chair)
23. Kyoung Joon Chang, 2007, Chair
24. Alex Knafl, 2007, Chair
25. Manbae Han, 2007, Co-Chair (with S. Bohac)
26. Melody Papke, 2007, Co-Chair with Jun Ni
27. Andreas Malikopoulos, 2007, Co-Chair (with P. Papalambros)
28. Jonathan Hagena, 2007, Co-Chair (with Z. Filipi)
29. Robert Prucka, 2007, Co-Chair (with Z. Filipi)
30. Orgun Guralp, 2008, Co-Chair (with Z. Filipi)
31. Chaitanya Sampara, 2008, Co-Chair (with E. Bissett, GM)
32. Yanbin Mo, 2008, Chair
33. Shawn Grannell, 2008, Co-Chair (with S. Bohac)
34. Andrew Ickes, 2009, Co-Chair (with S. Bohac)
35. Hee Jun Park, 2009, Co-Chair (with D. Jung)
36. Seung Hwan Keum, 2009, Co-Chair (with H. Im)
37. Byungchan Lee, 2009, Co-Chair (with D. Jung)
38. Will Northrop, 2009, Co-Chair (with S. Bohac)
39. Michael Smith, 2010, Co-Chair (with S. Bohac)
40. Jason Martz, 2010, Chair
41. Sung Jin Park, candidate, 2011 (expected), Co-Chair (with D. Jung)
42. Mehdi Abarham, candidate, 2011 (expected), Co-Chair (with J. Hoard)
43. Matt Spears, candidate, 2011(expected), Chair
44. Jerry Fuschetto, candidate, 2011 (expected), Chair
45. Russel Truemner, pre-candidate, 2011(expected), Co-Chair (with R. Beck)
46. Stefan Klinkert, pre-candidate, 2011 (expected), Co-Chair (with S. Bohac)
47. Sotiris Mamalis, pre-candidate, 2012 (expected), Co-Chair (with A. Babajimopoulos)
48. Robert Middleton, pre-candidate, 2013 (expected), Chair
49. Kevin Zaseck, pre-candidate, 2013 (expected), Co-Chair (with Z. Filipi)
50. Janardhan Kodavasal, pre-candidate, 2013 (expected), Co-Chair (with A. Babajimopoulos)
51. Prasad Shigne, candidate, 2013 (expected), Co-Chair (with A. Babajimopoulos)
52. Ashwin Salvi, pre-candidate, 2013 (expected), Co-Chair (with Z. Filipi)
53. Elliott Alexander Ortiz Soto, pre-candidate, 2013 (expected), Chair
54. Vijai Manikandan, candidate, 2013 (expected), Chair
55. Luke Hagen, pre-candidate, 2013 (expected), Chair

56. Brandon Lee, pre-candidate, 2013 (expected), Co-Chair (with A. Babajimopoulos)

Ph. D. Committees Chaired at University of Illinois in Urbana-Champaign

1. Qiong Li, 1991, Chair
2. Leonard Shih, 1992, Chair
3. Panos Tamamidis, 1992, Chair
4. Constantine Varnavas, 1994, Chair
5. Douglas Baker, 1995, Chair
6. Michalis Syrimis, 1996, Chair

M. S. Committees Chaired at University of Michigan

1. James Wallace, 1997, Chair
2. Michael Mshar, 1998, Chair
3. Scott Fiveland, 1999, Chair
4. George Seaward, 2000, Chair
5. Chris Depcik, 2000, Chair
6. Salih Mahameed, 2001, Chair
7. Ron Grover, 2001, Chair
8. Selim Buyuktur, 2001, Co-Chair (with M. Wooldridge)
9. Cheol Su Lee, 2001, Chair
10. Brian Baldwin, 2001, Chair
11. Tim Jacobs, 2002, Chair
12. John Matsushima, 2002, Co-Chair (with Z. Filipi)
13. Aris Babajimopoulos, 2002, Chair
14. Christos Chryssakis, 2002, Chair
15. Berrin Daran, 2002, Co-Chair (with Z. Filipi)
16. Scott Thompson, 2003, Chair
17. Chad Jagmin, 2003, Co-Chair (with Z. Filipi)
18. Andrew Ickes, 2003, Chair
19. Matthew Leustek, 2003, Chair
20. Wesley Williamson, 2004, Co-Chair (with Z. Filipi)
21. Robert Prucka, 2004, Chair
22. Jonathan Hagena, 2004, Chair
23. Chaitanya Sampara, 2004, Chair
24. Orgun Guralp, 2004, Co-Chair (with Z. Filipi)
25. Gerald Fernandes, 2006, Co-Chair (with Z. Filipi)
26. Chandra Sandrasekaran, 2006, Co-Chair (with S. Bohac)
27. Steve Busch, 2007, Co-Chair (with S. Bohac)
28. Vijayaraghavan Shriram, 2007, Co-Chair (with Z. Filipi)
29. Alberto Lopez, 2008, Co-Chair (with S. Bohac)
30. Challa Prasad, 2008, Co-Chair (with A. Babajimopoulos)
31. Mark Hoffman, 2008, Co-Chair (with Z. Filipi)
32. Michael Smith, 2009, Chair
33. Anastasios Amoratis, 2009, Co-Chair (with A. Babajimopoulos)
34. Sotiris Mamalis, 2009, Chair

35. Ashwin Salvi, 2009, Co-Chair (with Z. Filipi)
36. Robert Middleton, 2009, Chair
37. Samuel Olesky, 2009, Chair
38. Elliott Alexander Ortiz Soto, 2010, Chair
39. Janardhan Kodavasal, 2010, Co-Chair (with A. Babajimopoulos)
40. Prasad Shigne, 2010, Co-Chair (with A. Babajimopoulos)
41. Jeremy Spater, 2010, Chair
42. Laura Manofsky, 2011 (expected), Chair
43. Ann Marie Lewis, 2011 (expected), Chair
44. Luke Hagen, 2011 (expected), Chair
45. Srinath Gopinath, 2011 (expected), Chair
46. Kyoung Hyun Kwak, 2011 (excepted), Co-Chair (with D. Jung)
47. Tejas Chafekar, 2011 (expected), Co-Chair (with J. Hoard)

M. S. Degrees Chaired at University of Illinois in Urbana-Champaign

1. Edward Badillo, 1989, Chair
2. Matthew Polishak, 1989, Chair
3. Michael Bonne, 1989, Chair
4. James McLeskey, 1989, Chair
5. Riadh Namouchi, 1990, Chair
6. Tarun Mathur, 1990, Chair
7. Constantine Varnavas, 1990, Chair
8. Francis Friedmann, 1990, Chair
9. Andrew Phillips, 1990, Chair
10. Kevin Wiese, 1990, Chair
11. Brian Bolton, 1990, Chair
12. Panos Tamamidis, 1990, Chair
13. Thomas Leone, 1990, Chair
14. Timothy Burt, 1990, Chair
15. Douglas Baker, 1991, Chair
16. Gregory Clampitt, 1991, Co-Chair (with White)
17. Daniel Clark, 1991, Chair
18. Evangelos Karvounis, 1991, Chair
19. Matthew Lipinski, 1992, Co-Chair (with White)
20. Michalis Syrimis, 1992, Chair
21. Matthew Schroder, 1993, Co-Chair (with White)
22. Donald Nakic, 1994, Co-Chair (with White)
23. George Papageorgakis, 1994, Chair
24. Scott Butzin, 1994, Chair
25. Cristopher Bare, 1995, Chair
26. Thomas Brunner, 1995, Chair
27. Paul Herring, 1995, Chair
28. Stani Bohac, 1995, Chair
29. Timothy Frazier, 1995, Chair

M. Eng. Automotive Projects Directed at University of Michigan
(ME 593/503, 4 credit hours)

1. Winter 1996; Fadi Kanafani
2. Winter 1996; Richard Sellschop
3. Spring 1996; Philip Glazatov
4. Spring 1996; David Silberstein
5. Fall 1996; Caleo Tsai
6. Fall 1997, Marc Allain
7. Winter 1997; Osvaldo Corona
8. Winter 1997; Fabien Redon
9. Winter 1997; Steven Siegal
10. Spring 1997; Eric Mokrenski
11. Winter 1998; Lee Choon Hyong
12. Winter 1998; Yu-Min Lin
13. Winter 1998; Faisal Mahroogi
14. Winter 1998; Bruno Vanzieleghem
15. Summer 1998; Yuri Rodrigues
16. Fall 1998; Claude Bailey
17. Fall 1998; John Emley
18. Fall 1998; Ghosh Ranajay
19. Fall 1998; Islam Kazi
20. Winter 1999; Stephanie Lacrosse
21. Winter 1999; Russell Thompson
22. Winter 1999; Carlos Armesto, Greg Christensen, Eugene Cox, John Dent
23. Winter 1999; John Joyce
24. Winter 1999; Marcus Branner
25. Winter 1999; Michael McGuire
26. Summer 1999; Steven Hoffman
27. Summer 1999; Alejandro Sales
28. Summer 1999; David Wheatley
29. Fall 1999; Todd Petersen
30. Fall 1999; John Matsushima
31. Fall 1999; Michelle Chaka and Mary Wroten
32. Fall 1999; Julie D'Annunzio, Timothy Veenstra, and Todd Glance
33. Winter 2000; Bhargav SriParakash
34. Winter 2000; Douglas Iduciani and Ronald Kruger
35. Winter 2000; Timothy Gernant, Allen Lehmen and Jeffrey Kaiser
36. Winter 2000; Brian Young, Mark Dipko and Andrew Slankard
37. Winter 2000; Stephen White
38. Winter 2000; Tomoyuki Takada, Mami Takada and Milton Wong
39. Winter 2000; Cristian Arnou and Soon Low
40. Winter 2000; Elaine Kelley
41. Spring 2000; Joseph Fedullo, Colin Roberts and John Celmins
42. Summer 2000; Frank Voorburg and Marie Mann
43. Summer 2000; Ping (Pete) Yu
44. Winter 2001; Jason Martz;
45. Winter 2001; Kwang Yong Kang
46. Summer 2002; Jonathan Jackson

47. Summer 2002; David Swain and Dan Yerrace
48. Winter 2009; Peter Andruskiewicz
49. Winter 2009; Dan Murray
50. Winter 2009; Amit Goje

AUTO 503 Capstone Special Project

1. Fall 2008, Peter Andruskiewicz, 3 credit hours
2. Winter 2009, Amit Goje, 3 credit hours

Ph.D. at Korea Advanced Institute of Science and Technology (KAIST), Korea

(carried-out in part at W. Lay Automotive Laboratory under my direction)
Tong Won Lee, 2003

Diplomarbeit at Technical University of Graz, Austria

(carried-out at W. E. Lay Automotive Laboratory under my direction)
Guntram Lechner, 1999
Alex Knafl, 2001

Studenarbeit at Rheinisch-Westfalische Technische Hochschule Aachen

(carried-out at W. E. Lay Automotive Laboratory under my direction)

Michalis Panagiotidis, 1999
Christof Schultze, 1999

Graduate Special Projects (ME 590) Directed at University of Michigan

1. Winter 1995; Teresa Schulke; 3 credit hours
2. Winter 1995, Fadi Kanafani; 3 credit hours
3. Winter 1995, Karl Ondersma; 3 credit hours
4. Spring/Summer1995; M. Mubbashir Abbas; 2 credit hours
5. Winter 1996-98; Paul L. Powell III; 6 credit hours
6. Fall 1997; Erik Koehler; 3 credit hours
7. Winter 1998; Kukwon Cho; 3 credit hours
8. Winter 1998; Scott Fiveland; 3 credit hours
9. Winter 1999; Russell Thompson, 3 credit hours
10. Winter 1999; Stephanie LaCrosse, 3 credit hours
11. Summer 1999; Thomas Veling, 3 credit hours
12. Fall 1999, John Matsushima, 3 credit hours
13. Winter 2000, Carlos Armesto, 3 credit hours
14. Winter 2000, Lee Byungchan, 3 credit hours
15. Winter 2000 and Winter 2001, Cheol Su Lee, 6 credit hours
16. Winter 2000, Jeff Sanko, 3 credit hours
17. Winter 2000, Ryan Nelson, 3 credit hours
18. Winter 2000, Selim Buyuktur, 3 credit hours
19. Winter 2000, George Seaward, 3 credit hours

20. Winter 2000, Ping Yu, 3 credit hours
21. Fall 2000, Marie Mann, 3 credit hours
22. Fall 2000, Matthew Schwab, 3 credit hours
23. Winter 2001, Cheol Su Lee, 3 credit hours
24. Winter 2002, Josh Richards, 3 credit hours
25. Winter 2002 and Fall 2002, Brett Thompson, 6 credit hours
26. Fall 2002, Mengkai Zhang, 3 credit hours
27. Fall 2003, Krishna Kumar, 3 credit hours
28. Fall 2003 and Winter 2004, Andreas Malikopoulos, 6 credit hours
29. Fall 2003 and Winter 2004, Christopher Morgan, 6 credit hours
30. Winter 2004, Mark Hoffman, 3 credit hours
31. Winter 2004, Weibin Zhu, 3 credit hours
32. Fall 2004, Seung Hwan Keum, 3 credit hours
33. Fall 2004, John Zeilstra, 3 credit hours
34. Fall 2004 and Winter 2005, Kwangsoon Choi, 6 credit hours
35. Fall 2004 and Winter 2005, Qi Wang, 6 credit hours
36. Fall 2004 and Winter 2005, Qingan Zhang, 6 credit hours
37. Fall 2005, Jarrod Robertson, 3 credit hours
38. Fall 2005, Gudiseva Satya Varun, 3 credit hours
39. Winter 2005, Stephen Busch, 3 credit hours
40. Winter 2005, Abigail Mechtenberg, 3 credit hours
41. Winter 2005, Richard Niedzwiecki, 3 credit hours
42. Winter 2005, Choi Kwangsoon, 3 credit hours
43. Winter 2006, Nikolas Anderson, 3 credit hours
44. Winter 2007, David Ault; 3 credit hours
45. Winter 2007, Michael Christianson, 3 credit hours
46. Winter 2007, Matthew Freddo, 3 credit hours (with S. Bohac)
47. Winter 2007, Dong Han, 3 credit hours
48. Winter 2007, Stefan Klinkert, 3 credit hours (with S. Bohac)
49. Winter 2007, Mahesh Kumar Madurai. 3 credit hours
50. Winter 2007, Robert Middleton, 3 credit hours
51. Winter 2007, Challa Prasad, 3 credit hours (with A. Babajimopoulos)
52. Winter 2007, Ashutosh Sajwan, 3 credit hours (with S. Bohac)
53. Winter 2007, Jaskirat Singh, 3 credit hours (with D. Jung)
54. Winter 2007, Ashwin Salvi, 3 credit hours (with Z. Filipi)
55. Winter 2007, Vishnu Nair, 3 credit hours
56. Fall 2007; Vivek Srinivasan Narayanan; 3 credit hours
57. Winter 2008, Ramamurthy Vaidyanathan; 3 credit hours
58. Spring 2008, Alphonso King, 6 credit hours
59. Fall 2008, Amit Goje, 3 credit hours (with J. Hoard)
60. Fall 2008, Doohyun Kim, 3 credit hours
61. Fall 2008, Kyoung-Hyun Kwak, 3 credit hours
62. Fall 2008, Saktish Sathasivam, 3 credit hours
63. Fall 2008, Prasad Shingne, 3 credit hours
64. Winter 2009, Sourabh Goel, 3 credit hours
65. Winter 2009, Chang-Ping Lee, 3 credit hours
66. Winter 2009, Kevin Zaseck, 3 credit hours
67. Winter 2009, Elliott Ortiz-Sotto, 3 credit hours
68. Fall 2009, Vishnu Vitala, 3 credit hours

69. Winter 2010, Tejas Chafekar, 3 credit hours (with J. Hoard)
70. Fall 2010, Saradhi Rengarajan, 3 credit hours (with J. Hoard)

Undergraduate Special Projects (ME 490) Directed at University of Michigan

1. Winter 1995, Maurice Moulton; 3 credit hours
2. Winter 1995; George Papageorgakis; 3 credit hours
3. Winter 1996; David Messih; 3 credit hours
4. Winter 1996; Eric Morenski; 3 credit hours
5. Winter 1996; Benedict J. Baladad; 3 credit hours
6. Winter 1996; Kevin Ferraro; 3 credit hours
7. Spring 1997, Andreas Athanassopoulos, 3 credit hours
8. Fall 1998, Ryan Nelson, 3 credit hours
9. Winter 1999; Nicholas Bellovary and Daniel Kulick, 3 credit hours
10. Winter 1999; Daniel Herrera and Joel Hartter, 3 credit hours
11. Winter 1999; Larry Mercier and Reza Sharifi, 3 credit hours
12. Winter 2000; Nicolas Wetzler, 3 credit hours
13. Winter 2001; Andrew Ickes, 3 credit hours
14. Winter 2002; Keith DeMaggio, 3 credit hours
15. Fall 2003; Marvin (Bob) Riley
16. Fall 2004; Katherine Chia-Chun Ho, 3 credit hours
17. Fall 2004, Liang Xue, 3 credit hours
18. Winter 2005, Levi Roodvoets, 3 credit hours
19. Fall 2005; Erin Robbins, 3 credit hours
20. Winter 2006; David Ault, 3 credit hours
21. Winter 2006; Tommaso Gomez, 3 credit hours
22. Winter 2007; Daniel Murray, 3 credit hours
23. Spring 2007, Dimitri Karatsinides, 2 credit hours
24. Winter 2009; Anthony Mansoor, 3 credit hours
25. Winter 2009, Lucas Vanderpool, 3 credit hours

ME 450 Senior Design Project

1. Winter 2006, Dan Murray, Chris Marchese, Dave Ault, Randy Jones, "Design of a Hydraulic Dynamometer," 3 credit hours
2. Winter 2007, Qioghui Fung, Chun Yang Ong, Chee Chian Seah, Joann Tung, "Heated Catalyst Test-Rig for Single Cylinder Engine"

Undergraduate Research Opportunity Program (UROP)

1. Fall 2006, Christine Siew, "Determination of Operational Limits and Stability Analysis of HCCI Engine Using 1-D Simulation"
2. Fall 2006, Nathan Shoemaker, "Challenge X- Crossover to Sustainable Mobility"

CONTIBUTIONS TO RESEARCH

Major Research Accomplishments

Dr. Assanis' research interests lie in the thermal sciences and their applications to energy conversion, power and propulsion, and automotive systems design. His research focuses on analytical and experimental studies of the thermal, fluid and chemical phenomena that occur in internal combustion engines, after-treatment systems, and fuel processors. His efforts to gain new understanding of the basic energy conversion processes have made significant impact in the development of energy and power systems with significantly improved fuel economy and dramatically reduced emissions. His group's research accomplishments have been published in over 250 articles in journals and international conference proceedings. More specifically:

- Over the past 25 years, he has made major contributions in modeling and computer simulation of internal combustion engine processes and systems, under steady-state and transient operation, and in carrying-out sophisticated in-situ experimental techniques, applicable to operating engine combustion chambers, to validate their fidelity. His innovative work has shed light into complex fuel-air mixing, combustion, pollutant formation and transient heat transfer phenomena in metal and ceramic-insulated engine combustion chambers. His simulation models and experimental insights are used by engine researchers and developers (e.g., General Motors, Caterpillar, Argonne, Lawrence Livermore and Sandia National Laboratories) to improve vehicle fuel economy while at the same time satisfying ultra-stringent emissions standards.

- His group has pioneered the integration of high fidelity engine models with driveline and vehicle models and used these comprehensive tools for realistic assessment and design optimization of conventional and hybrid powertrain systems. His engine-in-vehicle simulation methodologies have contributed significantly to the dual need-dual use heavy-duty industry/U.S. Army ground mobility mission through the development and optimization of advanced propulsion systems with 2-3 times higher fuel efficiency and ultra low smoke and particulate emissions.

- He has made lasting contributions to the fundamental understanding of the chemical and physical processes that govern the operation of Homogeneous Charge Compression Ignition (HCCI) engines and their exhaust aftertreatment systems. His revolutionary insights make possible to operate engines in ultra clean, low temperature combustion, fuel economical regimes that constitute a paradigm shift from the traditional, high temperature, pollutant forming engine combustion. His HCCI combustion strategies and patents have assisted industry to improve fuel economy of clean gasoline and diesel cars by 15%-20%, while virtually eliminating NOx and particulate emissions.

- Over the past 15 years, Dr. Assanis has led the efforts to revitalize the University of Michigan's automotive engineering activities and transformed the Walter E. Lay Automotive Laboratory into a beehive of research activity (see the URL link:

http://me.engin.umich.edu/autolab/). He has initiated large-scale projects involving partnerships among academia, government and industry, led the fundraising efforts through writing major proposals, and directed the research activities. He has collaborated extensively with faculty members, research scientists and post-doctoral scholars from various Universities and disciplines. He has directed the research of more than 50 Ph.D. and more than 100 MS and M.Eng. graduate students. His group's research accomplishments have been published in over 250 articles in journals and international conference proceedings. His group's engine and powertrain system simulations are used in industry, academia and government.

Grants and Contracts

Dr. Assanis has been the project director, principal or co-principal investigator for more than $100M in grants and contracts funded by automotive industry (General Motors, Ford Motor Co., Chrysler LLC and DaimlerChrysler Corporation, Mitsubishi Motors Co., Honda Motor Co., Borg Warner, Ricardo), the heavy-duty truck industry (Detroit Diesel Corporation, Caterpillar, Inc., International, Cummins, Caterpillar, Yanmar Diesel Engine Co, Komatsu), the oil industry (ExxonMobil Corporation, Lubrizol, Amoco Oil, Chevron, Ethyl Corporation), the U.S. government (Department of Defense, Department of Energy, NASA, EPA, National Science Foundation) and National Laboratories (Sandia, Argonne). Major collaborative research partnerships he has led or co-led include:

- Department of Energy, Office of Policy and International Affairs, "U.S.-China Clean Energy Research Center - Clean Vehicle Consortium CERC-CVC," Sept. 2010-Sept. 2015. The strategic intent of the CERC-CVC is to forge a strong partnership between the U.S. and China, the largest greenhouse gas emitters and the largest existing and emerging vehicle markets, for breakthrough research and development. The CERC-CVC is led by the University of Michigan in partnership with Ohio State University, M.I.T., national labs (Sandia National Laboratories, Oak Ridge National Laboratory, Argonne National Laboratory, Joint BioEnergy Institute, Fraunhofer Institutes, Germany), and industry (Ford Motor Company, General Motors, Cummins Engine Co., Toyota Motor Co., Chrysler, Cummins, MAGNET, A123, American Electric Power, First Energy and the Transportation Research Center). The total value of the U.S. effort is nearly $30M, of which the US DOE will contribute $12.5M over a five-year period, and industry and academia will contribute $17M. The Chinese government will match the US effort with a $25M of funding to a consortium of Chinese academic partners, led by Tsinghua University, and industry.

- General Motors-University of Michigan Engine Systems Research Collaborative Research Laboratory (GM/UM ESR CRL). This successful research partnership between the two institutions, initiated in 1998 and currently in its third, five-year phase ($15M in total funding, 1998-2013) uses the special expertise of UM to conduct fundamental research into core competitive areas for GM in order to significantly improve fuel economy and dramatically reduce emissions of next generation engines. The CRL has also motivated the growth and strengthening of additional areas of excellence of importance to GM and commensurate with the scholarly expertise and intellectual pursuits of the University faculty. As of December 2010, Professor Assanis has stepped down as GM-UM ESR CRL Founding Co-Director to become the Founding Director for the United States Clean Vehicle Consortium, U.S.-China Clean Energy Research Center, 2010-2015.

- UM-led Multi-University Consortium on Homogeneous Charge Compression Ignition (HCCI)/ Low temperature Combustion (LTC) Engine Research, funded since 2001 by the Department of Energy (approx. $10M of funding to 12/31/09). This innovative research holds the promise of delivering high fuel economy with dramatically reduced emissions through a paradigm-shift approach compared to the traditional, high temperature, pollutant forming engine combustion in today's engines. University of Michigan partners include Stanford, MIT, and UC Berkeley. In 2011, our consortium has won a third-phase DOE award (3 years, $3.75M) to explore high-pressure, lean burn (HPLB) combustion, with the potential to improve engine efficiency by 20-40%.

- Automotive Research Center, (ARC), a UM-led, eight-university, U.S. Army Center of Excellence founded in 1994 to advance the state-of-the-art modeling and simulation of military and civilian ground vehicles. The current third phase ($40M in funding, July 2004 – July 2010) emphasizes research into the design of vehicles propelled by next-generation powertrain systems for a variety of energy supply sources. The ARC is the most advanced university-based automotive research center in the country and has provided both educational opportunities and a unique cooperative partnership among the military, academia and the automotive industry. Current University partners include Clemson University, Oakland University, University of Alaska-Fairbanks, University of Iowa, Virginia Tech University, and Wayne State University. As of October 2009, Professor Assanis has stepped down as ARC Director to become the Director of the Michigan Memorial Phoenix Energy Institute.

Other Current Grants at The University of Michigan

Department of Energy, Office for Energy Efficiency and Renewable Energy, Robert Bosch LLC, AVL Powertrain Engineering Inc., University of Michigan and Stanford University, "**A**dvanced **C**ombustion **C**ontrols – **E**nabling **S**ystems and **S**olutions (ACCESS) for High Efficiency Light Duty Vehicles, $24,000,000, Project Director: Hakan Yilmaz (Bosch); Co-PI and Lead for Combustion Modeling: Dennis Assanis; my group's portion of the budget $4,000,000 ($2,000,000 from DOE, $680,360 from Bosch, $480,000 from AVL and $839,640 from UM), 4/1/2010- 6/30/2014.

Department of Energy, Office for Energy Efficiency and Renewable Energy, "A University Consortium for Efficient and Clean High Pressure Lean Burn

Engines," The University of Michigan in partnership with Massachusetts Institute of Technology and University of California-Berkeley, 10/1/09-8/31/12, $3,750,000, Principal Investigator and Consortium Director.

Collaborative Development of Clean Diesel Exhaust Aftertreatment System Through Modeling and Testing, Michigan Economic Development Corporation, 21st Century Jobs Fund, $1,650,000, 1/1/07-6/30/10, Principal Investigator (proposal selection process conducted by American Association for the Advancement of Science; 61 awards from 505 submitted proposals).

General Motors R&D Center, "Modeling and Experimental Study of Boosted HCCI Engine," 7/1/07-6/30/2011, $1,400,000, Principal Investigator.

Ford Motor Company, "EGR Cooler Fouling Research," 4/1/10-12/31/11, $281,000, Principal Investigator.

U.S. Environmental Protection Agency, "Center for Engineering Excellence through Hybrid Technology," 11/1/09-10/31/12, $1,560,000, Co-Principal Investigator; PI: Z. Filipi.

University of Tennessee-Battelle, LLC., "Simulation of High Efficiency Stoichiometric GDI Combustion," 5/1/10-4/30/11, $100,000, Principal Investigator.

ConocoPhillips, Inc., "Fuel Effects on HCCI Combustion Limits," 6/30/2011, $100,000, Principal Investigator.

Michigan Public Service Commission, "Integrated Assessment of Feasibility and Deployment of Offshore Wind Technologies in the Great Lakes," 1/1/11-12/31/12, $800,000, Principal Investigator.

Competed for

National Science Foundation, "A Proposal for the Establishment of an Engineering Research Center for Carbon Neutral Vehicles (ERC-CNV)", The University of Michigan in partnership with Massachusetts Institute of Technology, University of California-Berkeley, University of Illinois at Urbana-Champaign, Michigan State University, North Carolina A&T State University, 9/1/08-8/31/13, $18,500,000, Principal Investigator and ERC Director; invited among 34/143 pre-proposals to submit a full proposal, and reached site visit round of 8 finalists.

Past Grants

Automotive Research Center (ARC) of Excellence in Modeling and Simulation of Ground Vehicles, Department of Defense: Phase I: 9/94-7/98,

$9,000,000, Co-Principal Investigator and *Deputy Director (1/96-7/98)*; Phase II: 7/98-6/04, $25,000,000, Co-Principal Investigator (7/98-9/02) and Principal Investigator (9/02-6/04); *Deputy Director (7/98 to 9/00) and Director (9/00-6/04).*

Experimental Investigation of Heat Rejection Characteristics of I-4 and V-6 Engine Designs, Ford Motor Co., 1/95 to 6/96, $142,000, Principal Investigator.

Prediction of Engine Heat Rejection, Ford University Research Program, 1995, $50,000 (unrestricted grant), Principal Investigator.

Direct Injection of Natural Gas: In Cylinder CFD Computations, DOE/NASA, 1/95 to 12/96, $214,506, Principal Investigator

Engine Heat Transfer and Engine/Fuels Interaction Technology, Chevron Oronite Technology Group, 5/95 to 4/99, $8,000, Principal Investigator

Engine Friction Studies with Boundary-Friction Reducing Additives, Mobil Technology Group and ExxonMobil Research and Engineering Company, 1/96-8/15/00, Total Funding $919,362, (*$183,540, 1/96-6/96; $135,822, 6/96-5/97; $250,000, 1/97-12/97; $200,000, 1/98-12/98; $100,000, 1/99-6/99; $50,000, 1/00-8/00)*, Principal Investigator.

Experimental Investigation of Heat Rejection Characteristics of Diesel Engine Designs, Ford Motor Co., 6/96-6/97, $20,000, Principal Investigator.

Study of Unburned Hydrocaron Emissions Mechanisms, Ricardo, 1997, $90,000 (gift), Principal Investigator.

Direct Injection of Natural Gas: In Cylinder CFD Computations, SANDIA, 3/97-2/98, $25,000, Principal Investigator.

Fuel Economy and Power Benefits of Cetane-Improved Fuels in Heavy-Duty Diesel Engines, Ethyl, 1997, $20,000 (gift), Principal Investigator.

Investigation of Thermal and Strength Characteristics of Metal Matrix Composite Pistons for Heavy-Duty Diesel Engines, Focus Hope, 1997-98, $60,000, Principal Investigator.

Effect of Metal Matrix Composite Liners on Engine Friction and Wear, Inco Limited, 1997-99, $50,000 (gift), Principal Investigator.

Optimizing the Performance and Emissions of a Direct-Injection Spark-Ignition Engine Using Multi-Dimensional Modeling, Honda Initiative Grant Program, 8/1/97-7/31/98, $25,000, Principal Investigator.

General Motors/UM Collaborative Research Laboratory (formerly Satellite Research Laboratory), 5/98-12/31/02, $5,000,000, GMCRL Co-Principal Investigator and Director, Advanced Powertrain Systems Division.

Effect of Exhaust Valve Opening on Cold Start Hydrocarbon Emissions, Ford Motor Company, 6/98 to 12/01, Total Funding $380,000 *($230,000, 6/98-12/99; $150,000, 1/00–12/00*), Principal Investigator.

Ricardo Single Cylinder Research Engines, Mobil Technology Company, 9/1/98, $230,000 (gift), Principal Investigator.

Optimizing the Performance and Emissions of Direct-Injection Compression-Ignition Engines Using Multi-Dimensional Modeling, EPA, 9/1/98-8/31/99, $40,000, Principal Investigator.

Diesel Spray Combustion Modeling, Yanmar Diesel Engine Company, Japan, 9/1/98, $27,000 (gift), Principal Investigator.

Using Chemical Kinetics to Simulate Engine Performance and Emissions, Caterpillar, Inc., 1/1/99-12/31/99, $40,000 (gift), Principal Investigator.

Mixture Preparation and Nitric Oxide Formation in a GDI Engine Studied by Combined Laser Diagnostics and Numerical Modeling DOE/Sandia National Laboratory, 4/1/1999-3 /31/2002, $383,505, Co-Principal Investigator.

Development of Pressure Reactive Piston Technology for Improved Efficiency and Low NOx Emissions in Spark-Ignition (SI) and Compression Ignition (CI) Engines, Ford Motor Company/DOE PNGV Program, 10/12/99-5/31/2003, $436,825, Principal Investigator.

In Cylinder Pressure Sensors Using Thin Film Shape Memory Alloys, Orbital Research, 6/00-8/31/02, $120,000, Principal Investigator.

Systems Approach for Demonstrating Very Low Nox Emissions from a Direct-Injection Compression-Ignition (CIDI) Engine with a NOx Catalyst, EPA, 1/01-6/30/02, $100,000, Principal Investigator.

Concurrent Design of Next Generation Powertrains, Manufacturing Processes and Materials: A Simulation-Based Approach, US ARMY/TACOM under the Dual Use Science and Technology program DUST 2000, 4/3/01-4/2/03, $3,000,000, Co-Principal Investigator.

Simulation-Based Design and Demonstration of Next Generation Advanced Diesel Technology, Ford Motor Company/US ARMY TACOM under the Dual Use Science and Technology program DUST 2001, $2,420,000, 9/1/01 to 12/31/03, Principal Investigator.

A University Consortium on Homogeneous Charge Compression Ignition, Low Temperature Combustion for High Efficiency, Ultra-Low Emission

Engines, The University of Michigan in partnership with Massachusetts Institute of Technology, Stanford University, and University of California-Berkeley, Department of Energy, Phase I: 10/1/01-3/31/06, $4,800,000, Principal Investigator and Consortium Director.

General Motors/UM Collaborative Research Laboratory on Engine Systems Research, “Advanced Diesel Combustion System Optimization Tools Implementation,” 6/1/04-8/31/04, $17,160, Principal Investigator and GMCRL Co-Director.

General Motors/UM Collaborative Research Laboratory on Engine Systems Research, “Advanced Diesel Combustion System Development and Measurement of Hydrocarbon Species and Unregulated Emissions from Diesel Engines Operating in Advanced Combustion Modes,” 9/1/03-8/31/04, $116,206, Principal Investigator and GMCRL Co-Director.

General Motors/UM Collaborative Research Laboratory on Engine Systems Research, “Experimental Assessment of Design Concepts for Robust Spray-Guided Stratified-Charge Combustion,” 8/1/04-7/31/05, $135,168, Principal Investigator and GMCRL Co-Director.

Precision Heat Management in SI Engines, DaimlerChrysler Challenge Fund Project, $180,000, 9/1/01 to 12/31/04.

Detailed Exhaust Hydrocarbon Measurements in a Multi-Cylinder Engine, Ford Motor Company, 9/1/03 to 8/31/05, $98,000, Principal Investigator.

Engine-In-Vehicle Modeling, Navistar, 1/1/99-12/06, $300,000, unrestricted grant, Co-Principal Investigator.

General Motors/UM Collaborative Research Laboratory on Engine Systems Research, “PCCI Diesel Engine Combustion and Aftertreatment Systems,” 9/19/2006, $85,000, unrestricted grant, Principal Investigator.

Fuel Processors for PEM Fuel Cells, Department of Energy, 10/01-9/06, $4,545,471, Co-Principal Investigator.

Eaton Corporation Innovation Center, “Assessment of the NOx Reducing Potential of NOx Adsorber-NH3 SCR Exhaust Aftertreatment Systems,” Phase I: 7/1/04 to 6/30/05, $114,876; Phase II: 7/1/05-12/31/06, $60,000, Principal Investigator.

General Motors/UM Collaborative Research Laboratory on Engine Systems Research, “Discovery Project: Free Piston Linear Alternator,” 6/1/05-8/31/07, $528,245, Principal Investigator.

Investigation of VVT Fuel Economy and Emissions Benefits under Cold-Start, Idle and Low Load Conditions, DaimlerChrysler Challenge Fund Project, 1/1/05 to 6/30/08, $300,000, Principal Investigator.

U.S. Environmental Protection Agency, “Integrated Hydraulic Hybrid Propulsion System and Advanced Components for Maximizing Fuel Efficiency and Emissions Benefits,” 4/2006-10/2009, $226,000, Co-Principal Investigator; PI: Z. Filipi.

Advanced Powertrain Modeling, Borg Warner, 1/06-6/10, $300,000, Principal Investigator.

Ford Motor Company, “Development of Diesel EGR Cooler Fouling Model,” Ford-UM Alliance, 9/1/07-12/31/09, $200,000, Principal Investigator.

Grants and Contracts at University of Illinois in Urbana-Champaign

Effect of Combustion Chamber Insulation on Turbocharged Diesel Engine Performance, UIUC-Research Board, 3/20/86 - 6/30/87, $20,000 (grant), Principal Investigator

Intake Valve Event Optimization for Specified Engine Operating Conditions, General Motors Pontiac Group, 8/21/86 to 6/30/88, $31,000, Co-Principal Investigators: J. E. Peters and D.N. Assanis, Project Director: D.N. Assanis

Development of a Modern Engine Test Cell for Studies of Low-Heat-Rejection Engine Performance, UIUC-Research Board, $6,000 (grant), 1/15/87 to 1/15/88, Principal Investigator

NSF, An Experimental and Analytical Study of Unsteady Heat Transfer in Low-Heat-Rejection Engine Combustion Chambers, $69,983, 7/1/87 to 11/30/89, Principal Investigator

Development of an Integrated Rankine Bottoming Cycle for Diesel Engine Exhaust Heat Recovery, UIUC-Research Board, $7,624 (grant), 8/21/87 to 5/21/88, Principal Investigator

Adiabatics, Inc., Development and Use of a Computer Simulation Code for LHR Vehicle Fuel Economy, $30,926, 9/1/87 to 7/31/88, Co-Principal Investigators: D. N. Assanis, R. A. White, Project Director: D.N. Assanis

Analysis and Testing of Ceramic-Coated Engine Components, Adiabatics, Inc., $14,466, 9/1/87 to 12/31/88, Principal Investigator

Fluidized Bed Heat Recovery from Diesel Engines, U.S. Army CERL, $13,692, 9/15/87 - 5/31/88, Principal Investigator

Engineering Research Equipment Grant: A Modern Single-Cylinder Engine Test Facility for Diesel Engine Research, NSF, $51,400 (equipment grant), from 5/1/88 to 10/31/89, Principal Investigator

Presidential Young Investigator Award: Engine Combustion and Emissions Studies, NSF, $312,500, 6/88 to 12/93, Principal Investigator

A Modern Single Cylinder Diesel Research Engine, Caterpillar, $27,000 (gift), 7/7/88, Principal Investigator

Development of Multi-Dimensional Heat Transfer Models for LHR Engine Studies, National Center for Supercomputing Applications, 35 CPU hours on CRAY X/MP, 3/88 to 12/89, Principal Investigator

Combustion and Emissions of Low-Heat-Rejection Diesel Engines, $129,223, U.S. Army TACOM, 8/88 to 8/90, Principal Investigator

The Effect of Light Weight Reciprocating Components on Engine Combustion, Frictional Losses, and Heat Transfer, Chrysler, 8/88 - 8/90, $115,992, Principal Investigator

An Optical Table for Laser Velocimetry, $6,311 (gift), Newport Corp., from 4/89, Principal Investigator

Support for Women, Minorities, and Disabled Engineering Research Assistants, NSF, 2/89 - 2/90, $4,958, Principal Investigator

Development of an Improved Combustion Model for Use in a Multi-dimensional Engine Simulation, National Center for Supercomputing Applications, 90 CPU hours on CRAY X/MP and CRAY 2, 12/89 - 12/90, Principal Investigator

An Experimental and Analytical Study of Unsteady Heat Transfer in LHR Engines - REU Supplement, NSF, 2/1/90 to 7/31/90, $8,973, Principal Investigator

Investigation of a Fluidized Bed Heat Exchanger, U.S. Army CERL, 8/90 to 5/91, $16,935, Principal Investigator

Development of a Hydrocarbon Emissions Model for Multi-Dimensional Engine Simulation, National Center for Supercomputing Applications, 80 CPU hours on CRAY X/MP and CRAY 2, 4/90 - 4/91, Principal Investigator

Effect of Reed Valves in the Intake Ports on SI Engine Performance and Knock, Ford Motor Company, 8/21/90 to 12/93, $169,377, Co-Principal Investigators: D.N. Assanis, J. E. Peters, R. A. White, Director: D. N. Assanis

A Study of Fuel-Air Distribution in the Intake System of a Spark-Ignited Natural Gas Engine, Cummins, 8/21/90 - 5/31/94, $140,000 (gift), Co-Principal Investigators: D. N. Assanis, R. A. White

Lignin-Augmented Bituminous Coal Depolymerization: A Route to Clean Fuels, Center for Research on Sulfur in Coal, $105,036, Co-PI, 8/21/90 to 8/31/91, Co-Principal Investigators: D. N. Assanis, C. Kruse, PD: C. Kruse

Prediction of 3-D Turbulent Flows Using a BFC Computer Code, National Center for Supercomputing Applications, $24,000 and 50 CPU hours on CRAY 2, 9/90 - 8/92, Principal Investigator

Joint Research Program between Mitsubishi Motors Corp. and University of Illinois, Mitsubishi Motors Corp., $340,000 6/1/91 to 5/31/93, Co-Principal Investigators: D. N. Assanis, R. A. White, H. Sehitoglu, D. Socie, Project Director: D. N. Assanis

Octane Requirement Increase and its Relation to Combustion Chamber Deposits, Amoco Oil Company, $130,798, 9/1/91to 12/93, Co-Principal Investigators: D. N. Assanis, R. A. White, Project Director: R. A. White

Integrated Production/Use of Ultra Low Ash Coal, Center for Research on Sulfur in Coal, $148,959, Co-PI, 8/91- 8/92, Co-Principal Investigators: D. N. Assanis, C. Kruse, Project Director: C. Kruse

Development, Optimization, and Testing of a 3-D Computational Fluid Dynamics Code, National Center for Supercomputing Applications, 96 hours on CRAY Y-MP, 11/91 to 12/92, Principal Investigator

A Modern Set of Emissions Analyzers for Internal Combustion Engine Pollution Studies, UIUC Research Board, $42,000 (grant), 10/91, PI

Development of a Comprehensive Evaporation Model for Use in a Multi-Dimensional Engine Simulation, National Center for Supercomputing Applications, 85 CPU hours on CRAY X/MP and CRAY 2, 11/92 - 12/93, Principal Investigator

Effects of Combustion Characteristics on Heat Loss under Knocking and Non-Knocking Conditions, Mitsubishi Motor Company, 6/93 - 5/95, $200,085, Co-Principal Investigator: D. N. Assanis

An Improved Model for Droplet Evaporation in High Pressure Diesel Sprays, UIUC Research Board, $6,728 (grant), 6/93 to 12/93, Principal Investigator

Design of Low Distortion Insulated Piston/Liner System, Inco Ltd., $25,000 (gift), from 8/93 - 8/95, Principal Investigator

RISC-6000 Workstations for Computation and Visualization of Reactive Engine Flows, IBM, $39,888 (gift), from 12/93, Co-Principal Investigators: D. N. Assanis, R. A. White

Direct Injection of Natural Gas: In Cylinder CFD Computations, DOE/NASA, 1/94 to 12/94, $231,174, Co-Principal Investigators: D. N. Assanis, J. E. Peters, R. L. Lucht, Project Director: D.N. Assanis

Direct Injection of Natural Gas: In Cylinder Laser Measurements, GRI, 1/94 to 12/96, $488,178, Co-Principal Investigators: D. N. Assanis, J. E. Peters, R. L. Lucht, Project Director: R.L. Lucht

Prediction of Engine Heat Rejection, Ford University Research Program, from 1/94, $50,000 (grant), Principal Investigator

Evaluation of Hydrated Ethanol for DI Compression Ignition Engines, Illinois Department of Energy and Natural Resources, 1/94 to 6/96, $60,000 per year, Co-Principal Investigators: D. N. Assanis, C. Goering.

Publications

Articles in Refereed Journals, Transactions or Archives

1. D. N. Assanis, and J. B. Heywood, "Development and Use of a Computer Simulation of the Turbocompound Diesel System for Engine Performance and Component Heat Transfer Studies," selected for *SAE 1986 Transactions*, 95:2, 2.451-2.476, 1987. (Presented as SAE Paper 860329, SAE International Congress and Exposition, Detroit, MI, Feb. 24-28, 1986; and included in *The Adiabatic Diesel Engine: Global Developments*, SAE Special Publication 650, 95-120, 1986.)

2. Assanis, D. N., and Heywood, J. B., "Simulation Studies of the Effects of Low-Heat-Rejection on Turbocompound Diesel Engine Performance," *International Journal of Vehicle Design*, 8:3, 282-299, 1987. (Based on Presentation at 3rd International Conference on Turbocharging and Turbochargers, Institute of Mechanical Engineers, London, United Kingdom, May 6-8, 1986.)

3. Assanis, D. N., and E. Badillo, "Transient Heat Conduction in Low-Heat Rejection Engine Combustion Chambers," selected for *SAE 1987 Transactions,* 96:4, 4.82-4.92, 1988. (Presented as SAE Paper 870156, SAE International Congress and Exposition, Detroit, MI, Feb. 23-27, 1987; and included in *Adiabatic Engines and Systems*, SAE Special Publication 700, 153-163, 1987.)

4. Assanis, D. N., and E. Badillo, "Transient Analysis of Piston-Liner Heat Transfer in Low-Heat-Rejection Diesel Engines," selected for *SAE 1988 Transactions: Journal of Engines*, 97:6, 6.295-6.305, 1989. (Presented as SAE Paper 880189, SAE International Congress and Exposition, Detroit, MI, Feb. 29-March 4, 1988; and included in *Recent Developments in the Adiabatic Engine*, SAE Special Publication 738, 97-107, 1988.)

5. Assanis, D. N., "Effect of Combustion Chamber Insulation on the Performance of a Low-Heat-Rejection Diesel Engine with Exhaust Heat Recovery," *Journal of Heat Recovery Systems & Combined Heat and Power,* 9:5, 475-484, 1989. (Based on Paper 869486, presented at 21st Intersociety Energy Conversion Engineering Conference, San Diego, CA, Aug. 25-29, 1986.)

6. Assanis, D. N., and E. Badillo, "On Heat Transfer Measurements in Diesel Engines using Co-Axial Fast-Response Thermocouples," *ASME Transactions: Journal of Engineering for Gas Turbines and Power,* 111:3, 458-465, 1989. (Presented at ASME-ETCE Technical Conference, Houston, TX, Jan. 22-25, 1989; and included in *Basic Processes in Internal Combustion Engines,* ICE-6, 25-32, 1989.)

7. Assanis, D. N., "Thin Thermal Barrier Coatings for Internal Combustion Engine Components," *International Journal of Materials and Product Technology*, 4:3, 232-243, 1989. (Presented with R. Kamo and W. Bryzik as SAE Paper 890143, SAE International Congress and Exposition, Detroit, MI, Feb. 27 - March 3, 1989 and selected for *SAE 1989 Transactions: Journal of Engines*, 98:3, 131-136, 1990.)

8. Phillips, A., and D. N. Assanis, "A PC-Based Vehicle Powertrain Simulation for Fuel Economy and Performance Studies," *International Journal of Vehicle Design*, 10:6, 639-658, 1989. (An improved version of the simulation was presented with A. Phillips and P. Badgley in SAE Paper 900619, SAE International Congress and Exposition, Detroit, MI, Feb. 26-March 2, 1990; and selected for *SAE 1990 Transactions: Journal of Passenger Cars*, 99:6, 1991.)

9. Assanis, D. N. and M. Polishak, "Valve Event Optimization in a Spark-Ignition Engine," *International Journal of Vehicle Design*, 10:6, 625-638, 1989. (Presented at ASME-ICED Technical Conference, Dearborn, MI, Oct. 15-18, 1989; and selected for *ASME Transactions: Journal of Engineering for Gas Turbines and Power,* 112:3, 341-347, 1990.)

10. Assanis, D. N., and E. Badillo, "Evaluation of Alternative Thermocouple Designs for Transient Heat Transfer Measurements in Metal and Ceramic Engines," selected for *SAE 1989 Transactions: Journal of Engines*, 98:3, 1036-1051, 1990. (Presented as SAE Paper 890571, SAE International Congress and Exposition, Detroit, MI, Feb. 27 - March 3, 1989; and included in *Worldwide Progress on Adiabatic Engines, SAE Special Publication* 785, 169-184, 1990.)

11. Tamamidis, P., and D. N. Assanis, "Generation of Orthogonal Grids with Control of Spacing," *Journal of Computational Physics*, 94:2, 437-453, 1991.

12. Sekar, R. R., W. W. Marr, D. N. Assanis, R. L. Cole, T. J. Marciniak, and J. E. Schaus, "Oxygen Enriched Diesel Engine Performance: A Comparison of Analytical and Experimental Results," *ASME Transactions: Journal of Engineering for Gas Turbines and Power,* 113:3, 365-369, 1991. (Presented at ASME-ICED Technical Conference, Rockford, IL, Oct. 1990; and included in *New Technology in Large Bore Engines,* ICE-13, 57-62, 1990.)

13. Filipi, Z., and D. N. Assanis, "Quasi-Dimensional Computer Simulation of the Turbocharged Spark-Ignition Engine and its Use for Two and Four Valve Engine Matching Studies," selected for *SAE 1991 Transactions: Journal of Engines*, 100:3, 52-68, 1992. (Presented as SAE Paper 910075, SAE International Congress and Exposition, Detroit, MI, Feb. 25-March 1, 1991.)

14. Assanis, D. N., Wiese, K., Schwarz, E., and W. Bryzik, "The Effects of Ceramic Coatings on Diesel Engine Performance and Exhaust Emissions," selected for *SAE 1991 Transactions: Journal of Engines*, 100:3, 657-665, 1992.

(Presented as SAE Paper 910460, SAE International Congress and Exposition, Detroit, MI, Feb. 25-March 1, 1991.)

15. Varnavas, C., and D. N. Assanis, "The Effects of Spray, Mixing, and Combustion Model Parameters on KIVA-II Predictions," selected for *SAE 1991 Transactions: Journal of Engines*, 1488-1497, 100:3, 1992. (Presented as SAE Paper 911785, *SAE International Off-Highway and Powerplant Congress*, Milwaukee, WI, Sept. 9-12, 1991.)

16. Shih, L., and D. N. Assanis, "Implementation of a Fuel Spray Wall Interaction Model in KIVA-II," selected for *SAE 1991 Transactions: Journal of Engines*, 100:3, 1498-1512, 1992. (Presented as SAE Paper 911787, SAE International Off-Highway and Powerplant Congress, Milwaukee, WI, Sept. 9-12, 1991.)

17. Yerramareddy, S., Tcheng, D. T., Lu, S. C-Y., and D.N. Assanis, "Creating and Using Models for Engineering Design: A Machine Learning Approach," *IEEE Expert, Special Track on Machine Learning,* 52-59, June 1992.

18. Assanis, D.N., "The Effect of Thin Ceramic Coatings on Petrol Engine Performance and Emissions," *International Journal of Vehicle Design*, 13:4, 378-388, 1992. (Based on SAE Paper 900903, presented with T. Mathur at SAE 41st Annual Earthmoving Industry Conference, Peoria, IL, April 3-5, 1990; and selected for *SAE 1990 Transactions: Journal of Materials and Manufacturing*, 99:5, 1991.)

19. Assanis, D. N., and F. A. Friedmann, "A Thin-Film Thermocouple for Transient Heat Transfer Measurements in Ceramic-Coated Combustion Chambers," *International Communications in Heat and Mass Transfer,* 20, 459-468, 1993.

20. Karvounis, E., and D. N. Assanis, "The Effect of Inlet Flow Distribution on Catalytic Conversion Efficiency", *International Journal of Heat and Mass Transfer,* 36:6, 1495-1504, 1993.

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6. Assanis, D. N., "A Methodology for Characterizing the Thermal Behavior of Internal Combustion Engine Systems", invited presentation, *Proceedings of The Best of German/American Automotive Technology Conference,* Southfield, MI, June 27-28, 1995.

7. Assanis, D. N., "A Methodology for Characterizing the Thermal Behavior of Internal Combustion Engine Systems", invited presentation, Engineering Foundation Conference, Shonan Village, Japan, September 23-29, 1995.

8. Papageorgakis, G., Agarwal, A., and D. N. Assanis, "Multi-Dimensional Modeling of Natural Gas Injection, Glow Plug Ignition, and Combustion with the KIVA-3 Code: The Effect of Piston Crown Geometry," Sixth International KIVA Users Group Meeting, Detroit, MI, Feb. 25, 1996.

9. Papageorgakis, G., Agarwal, A., and D. N. Assanis, "Multi-Dimensional Modeling of Natural Gas Injection, Glow Plug Ignition, and Combustion with the KIVA-3 Code, Poster Session, Annual DOE Automotive Technology Development Customers' Coordination Meeting, Dearborn, MI, Oct. 28 - Nov. 1, 1996.

10. Assanis, D. N., "3-D Modeling of Engine Reacting Flows: Promises and Challenges," invited paper, Panel on Automotive Applications of CFD, Atlanta, 1996 ASME International Mechanical Engineering Congress and Exposition, Atlanta, GA, Nov. 17-22, 1996.

11. Papageorgakis, G., and D. N. Assanis, "Implementation and Assessment of Alternative Turbulence Models in KIVA-3," Seventh International KIVA Users Group Meeting, Detroit, MI, Feb. 25, 1996.

12. Assanis, D. N., "Engine Friction Measurements," invited presentation, Panel on Surface Engineering and Tribology, SAE International Congress and Exposition, Detroit, MI, Feb. 23-26, 1998.

13. Assanis, D. N., "Engine Friction Measurements," Keynote Presentation, DOE Workshop on Research Needs for Reducing Friction and Wear in Transportation, Argonne National Laboratory, March 22-23, 1999.

14. Delagrammatikas, G. and D.N. Assanis, "Development and Use of a Regenerative Braking Model in ADVISOR," ADVISOR User Conference Proceedings, Costa Mesa, CA, Aug. 24-25, 2000.

15. Assanis, D.N., Louca, L., and Z. Filipi, "Drivetrain Simulation and Modeling Based Upshift Control," Modern Advances in Automatic Transmission Technology TPOTEC, Ypsilanti, MI, Aug. 29-30, 2002.

16. Assanis, D. N. and S. Tung, "Overview of Engine Friction and Wear Measurements," Future Trends in Engine Design and Tribology, Society of Tribologists and Lubrication Engineers, Rochester, MI, August 22, 2001.

17. Assanis, D. N., "Modeling of Hybrid Vehicle Systems", invited presentation, 7th International Conference on *Present and Future Engines for Automobiles*, Delphi, Greece, May 27-31, 2001.

18. Assanis, D. N., "Discussion of the National Research Council Report on Corporate Average Fuel Economy," SAE President's Invited Panel, 2002 SAE International Congress and Exhibition, 2002 SAE World Congress, Detroit, MI, March 4-7, 2002.

19. Fiveland, S. and D. N. Assanis, "A Quasi-Dimensional HCCI Model for Performance and Emissions Studies," Ninth International Conference on Numerical Combustion, Sorrento, Italy, April 7-10, 2002.

20. Assanis, D. N., "Does the Internal Combustion Engine Have a Future?", The Advanced Power Technology Forum, Management Briefing Seminars 2002, Traverse City, MI, August 5-9, 2002.

21. Assanis D. N., "Does the Internal Combustion Engine Have a Future?", invited plenary speaker, session on "*Future Automotive Powertrains*," Global Powertrain Congress, Ann Arbor, MI, September 24-26, 2002.

22. Assanis, D.N., "Securing a Successful Academic Career," invited panelist, ASME IMECE, New Orleans, LA, November 17-22, 2002.

23. Bohac, S., Assanis, D.N., and H.L.S Holmes, "Speciated Hydrocarbon Emissions from a Contemporary Automotive Gasoline Engine and Local Ozone Production," Anachem Symposium, Livonia, MI, November 21, 2002.

24. Filipi, Z. S., Wu, B., Lin, C.C., and D. N. Assanis, "Fuel Economy Potential of Hydraulic Hybrid Propulsion Systems for Medium Trucks," SAE International Truck and Bus Meeting and Exhibition, Cobo Center, Detroit, MI, November 18-20, 2002.

25. Assanis. D.N., "Internal Combustion Engines and Hybrids: They are Here to Stay," Testimony to State of Michigan's Senate Technology and Policy Committee," Farnum Building, Lansing, MI, February 19, 2003.

26. Assanis, D.N., "A University Consortium on Homogeneous Charge Compression Ignition Engine Research," invited speaker, International Workshop on Advanced Combustion and Fuels," Argonne National Laboratory, Argonne, IL, June 16-17, 2003.

27. Assanis, D.N., "Major Research Issues," invited panelist, International Workshop on Advanced Combustion and Fuels," Argonne National Laboratory, Argonne, IL, June 16-17, 2003.

28. Vanzieleghem, B.P., Chryssakis, C.A., Grover, R.O., Assanis, D.N., Im, H.G., and V. Sick, "Gasoline Direct Injection Modeling and Validation with Engine Planar Laser Induced Fluorescence Experiments," 14th International Multidimensional Engine Modeling User's Group Meeting, Detroit, MI, March 2004.

29. Depcik, C., and D.N. Assanis, "One-Dimensional Catalyst Modeling and its Application to Urea SCR Devices," Seventh CLEERS Workshop, Detroit Diesel, Detroit, MI, June 2004.

30. Assanis, D.N., et al., "Clean and Controllable, Advanced Compression Ignition Engine System for Improved Power Density and Fuel Economy", plenary session presentation at the Annual ARC Conference on "Critical Technologies for Modeling and Simulation of Ground Vehicles", Ann Arbor, May 2004.

31. Babajimopoulos, A., Assanis, D.N., Flowers, D.L., Aceves, S.M., and R.P. Hessel, "A Fully Integrated CFD and Multi-Zone Model with Detailed Chemical Kinetics for the Simulation of PCCI Engines," 15th International Multidimensional Engine Modeling User's Group Meeting, Detroit, MI, April 2005.

32. Assanis, et al., "Engine-In-the-Loop Simulation: A Design and Evaluation Tool for Advanced Propulsion Systems", plenary session presentation at the Annual ARC Conference on "Critical Technologies for Modeling and Simulation of Ground Vehicles", Ann Arbor, May 2005.

33. Assanis, D. N., "Bridging the Gap between Fundamental Physics and Chemistry and Applied Models for HCCI Engines", invited presentation, 9th International Conference on *Present and Future Engines for Automobiles*, San Antonio, TX, May 29 to June 2, 2005.

34. Assanis, D. N., "Bridging the Gap between Fundamental Physics and Chemistry and Applied Models for HCCI Engines", invited presentation, 11th International Conference on *Diesel Engine Emissions Reduction DEER 2005*, Chicago, IL, August 21-25, 2005.

35. Leustek, M.E., Sethu, C., Bohac, S., Filipi, Z., and D.N. Assanis, "Crank-angle Resolved In-Cylinder Friction Measurements with the Instantaneous IMEP Method", Proceedings of World Tribology Congress III, Washington D.C., Sept. 2005.

36. Assanis, D.N., et al., "Integrative Approach to Advanced Propulsion System Design Using Simulation and Engine-In-the-Loop", plenary session presentation at the Annual ARC Conference on "Critical Technologies for Modeling and Simulation of Ground Vehicles", Ann Arbor, May 2006.

37. Assanis, D. N., "Low Temperature Combustion for High Efficiency Ultra Low Emissions Engines", invited presentation, 12th International Conference on *Diesel Engine Efficiency and Emissions Reduction DEER 2006*, Detroit, MI, August 20-24, 2006.

38. Assanis, D. N., "Analysis and Control of HCCI Engine Transient Operation Using 1-D Cycle Simulation and Thermal Networks", invited presentation, SAE HCCI Engine Symposium, San Ramon, CA, September 24-26, 2006.

39. Assanis, D. N., "Next Generation Powertrains and Fuels: Grand Challenges and Opportunities", invited presentation, UM Symposium on Energy Science, Technology and Policy, Ann Arbor, MI, February 13-14, 2007.

40. Assanis, D.N., "Energy Research: Grand Challenges and Opportunities," invited talk, Lehigh University, Bethlehem, PA, February 2, 2007.

41. Assanis, D.N., "Today's Students, Tomorrow's Engineers," invited panelist, SAE 2007 World Congress, Detroit, MI, April 16-19, 2007.

42. Assanis, D.N., et al, "Energy and Power for Military Vehicles: Alternative Fuels and Hybrid Propulsion", plenary session presentation at the Annual ARC Conference on "Critical Technologies for Modeling and Simulation of Ground Vehicles", Ann Arbor, May 2007.

43. Assanis, D. N., "On Modeling HCCI Engine Transient Behavior", invited presentation, 10th International Conference on *Present and Future Engines for Automobiles*, Rhodes, Greece, May 28 to June 5, 2007.

44. Assanis, D.N., "*TechKnow: Alternative Fuel Cars*," invited panelist, Power Center, Ann Arbor, MI, June 12, 2007.

45. Assanis, D.N., "Analysis and Control of HCCI Engine Transient Operation", invited presentation, Homogeneous Charge Compression Ignition (HCCI) Symposium, Lund, Sweden, September 12-14, 2007.

46. Assanis. D.N., "Low Temperature Combustion for High Efficiency, Ultra-Low Emission Engines" invited talk, University of Illinois at Urbana-Champaign, April 1, 2008.

47. Middleton, R. and D. N. Assanis, "Nitrogen Oxides Oxidation as a Function of Lean NO Trap Loading," 11th DOE Crosscut Workshop on Lean Emissions Reduction Simulation, University of Michigan - Dearborn, May 13 - 15, 2008.

48. Assanis, D.N., in collaboration with G. Lavoie and A. Babajimopoulos, "Advanced Combustion for High Efficiency Ultra-Clean Engines," Keynote Lecture, 6th US National Combustion Meeting, Ann Arbor, MI, May 17-20, 2009.

49. Assanis, D.N., Invited Panelist on "Secure, Low-Carbon Transportation System," Workshop on *Formulation of A Bipartisan Energy and Climate Policy: Toward an Open and Transparent Process*, The Howard H. Baker Jr. Center for Public Policy and the Widrow Wilson International Center for Scholars, Washington, DC, June 18-19, 2009.

50. Assanis, D.N., "On the Road to Clean and Efficient Powertrains," invited presentation, UMTRI Symposium on Powertrain Strategies for the 21st Century: How Are New Regulations Affecting Company Strategies?", Ann Arbor, MI, July 15, 2009.

51. Assanis, D.N., Invited Panelist on "Future Transportation and Energy Policy," 5th International IEEE Vehicle Power and Propulsion Conference VPPC 2009, Dearborn MI, September 10, 2009.

52. Assanis, D.N., Invited Keynote Speaker, "Advanced Combustion for High Efficiency Ultra Clean Engines," American Filtration Society, 4th Biennial Conference on Emission Solutions in Transportation, Ann Arbor, MI, October 5-8, 2009.

53. Assanis, D.N., Invited Keynoter for Opening Ceremony, "The Business of Plugging-In", Motorcity Hotel and Conference Center, October 19-21, 2009.

54. Assanis, D.N, Invited Panelist on "High Efficiency IC Engines," SAE 2009 Powertrains, Fuels and Lubricants Meeting, San Antonio, TX, November 2-4, 2009.

55. Assanis, D.N., Invited Panelist on Alternative Energy Sources, "Meeting the Energy Challenge: The Role of Biofuels in Solving Society's Largest Problem in the 21st Century", Energy for the Future Conference, University of Dearborn, MI, March 16, 2010

56. Assanis, D.N, Invited Panelist on "Pathways to High Efficiency IC Engines," SAE 2010 World Congress, Detroit, MI, April 13-15, 2010.

57. Assanis D.N., Invited Speaker, “Assessing Great Lakes Offshore Wind: A Partnership between the University of Michigan and Grand Valley State University,” University of Michigan Regents’ Meeting, Grand Rapids, MI, April 15, 2010.

58. Assanis, D.N., Ortiz-Soto, E., Babajimopoulos, A., and G. Lavoie, “Dual-Mode SI-HCCI Operation for Improved Drive-Cycle Fuel Economy: Engine Modeling and Map Generation Framework,” Invited presentation to USCAR, Southfield. MI, May 12, 2010.

59. Assanis, D. N., “The Road to Clean Vehicles,” invited lecture, Zhejiang Automotive Institute, Hangzhou, China, May 29, 2010.

60. Assanis, D.N, Invited Speaker on “Pathways to High Efficiency I.C. Engines,” 11th International Conference on Present and Future Engines for Automobiles, Shanghai, China, May 30-June 3, 2010.

61. Assanis, D.N., Invited Plenary Speaker, “Towards Carbon Neutral Vehicles,” Emissions 2010, Ann Arbor, MI, June 14-16, 2010.

62. Assanis, D.N., “A University Consortium on High Pressure Lean Combustion for Efficient and Clean Internal Combustion Engines,” 16th Directions in Engine-Efficiency and Emissions Research (DEER) Conference, September 27-30, 2010, Detroit, Michigan.

63. Assanis, D.N., Invited Speaker, “Thermodynamic Lessons Learned from Lean/Dilute Burn Diesels to Improve Gasoline Engine Efficiency,” invited presentation, Cummins Science and Technology Council Advisory Board Meeting, Columbus, IN, October 6-8, 2010.

64. Assanis, D.N., Invited Speaker, “U.S.-China Clean Energy Research Center for Clean Vehicles”, UMTRI Focus on the Future Automotive Research Conferences, Inside China: Understanding China’s Current and Future Automotive Industry, The University of Michigan League, Ann Arbor, MI, November 10, 2010.

65. Assanis, D.N., Invited Panelist, Erb Institute Conference, “Michigan-China Clean Tech: Collaboration and Competition in Energy, Smart Grid, Green Cities and Transportation,” The University of Michigan Union, December 10, 2010.

Books Edited

Uzkan, T., and Assanis, D. N., Editors, “Advanced Engine Simulations, Volume 1, *Proceedings of the 1997 ASME-ICE Spring Technical Conference*, ICE-Vol. 28-1, ASME, 1997.

Assanis, D.N., Papalambros, P.Y., and Bryzik, W., Guest Editors, Haug, E., Editor, Automotive Research Center Special Edition Issue, *Mechanics of Structures and Machines*, **27**:4, 1999.

Zhao, F., Asmus. T., Assanis, D. N., Dec. J. E., Eng, J. A., and P. M. Najt, *Homogeneous Charge Compression Ignition (HCCI) Engines: Key Research and Development Issues*, SAE PT-94, Society of Automotive Engineers, Warrendale, PA, 2003.

Assanis, D.N., Bryzik, W., Gorsich. D., and Haque, I., Guest Editors, Automotive Research Center Special Edition Issue, *International Journal of Heavy Vehicle Systems*, **11**:3/4, 372-402, 2004.

Cheng, W.K., Dibble, R., and D.N. Assanis, Guest Editors, *International Journal of Engine Research*, Special Issue on HCCI Engines, **6**:5, 2005.

Chapters in Books

Assanis, D.N., Borgnakke, C., Patterson, D.J., and Cole, D., "Internal Combustion Engines," *Marks' Standard Handbook for Mechanical Engineers*, pp. 9-90 to 9-121, 10th Edition, McGraw-Hill Book Company, 1996.

Assanis, D.N., Lavoie, G. A. and S. B. Fiveland, "HCCI Engine Modeling Approaches," pp. 529-655, published in *Homogeneous Charge Compression Ignition (HCCI) Engines: Key Research and Development Issues*, SAE PT-94, Society of Automotive Engineers, Warrendale, PA, 2003.

Assanis, D.N., Cole, D., Jacobs, T.J., and D.J. Patterson, "Internal Combustion Engines," *Marks' Standard Handbook for Mechanical Engineers*, pp. 9-93 to 9-127, 11th Edition, McGraw-Hill Book Company, 2007.

Chryssakis, A., Assanis, D.N. and F.X. Tanner, "Atomization Models," *Handbook of Atomization and Sprays: Theory and Applications*, Springer, 2011.

Reports

Assanis, D. N., "A Study of the Heat Transfer, Combustion and Emissions Characteristics of Low-Heat Rejection Diesel Engines," U.S. Army Tank-Automotive Command Research, Development and Engineering Center Technical Report No. 13589, June 1991.

Poola, R. B., Sekar, R., and D.N. Assanis, "Application of Oxygen-Enriched Combustion for Locomotive Engines, Phase I," Argonne National Laboratory Report ANL/ESD/TM-135, September 1996.

National Academy of Sciences Committee to Assess Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles; National Research Council; Transportation Research Board, "Technologies and Approaches to Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles," Washington, DC, The National Academies Press, September 2010.

Available electronically from the National Academies Press Web site at http://www.nap.edu/catalog.php?record_id=12845

President's Council of Advisors on Science and Technology (PCAST) Working Group on Energy Technology Innovation System, "Report to the President on Accelerating the Pace of Change in Energy Technologies through an Integrated Federal Energy Policy," November 2010.

Inventions and Patents

Church, C., Smith, F., and D.N. Assanis, "Use of Singlet Delta Oxygen to Enhance the Performance of Internal Combustion Engines, Diesel Engines in Particular," Patent No. 6,659,088, granted 12/9/2003.

Wu, B., Filipi, Z., Assanis, D.N., Kramer, D., Ohl, G., Prucka, M., and E. DiValentin, "Artificial Neural Networks for Estimating the Air Flow Rate through a VVT Engine", Invention Development Record P706964 disclosed 04/21/2004. Filed by a joint team of UM and DCX researchers.

Shih, A.J., Filipi, Z., and D.N. Assanis, "Pre-Turbocharging Catalyzed Porous Metal Foam Filter for Diesel Particulates Treatment", Invention Disclosure No. 2924 to UM Tech Transfer Office, July 2004.

Najt, P.M., Eng, J.A., Chang, J., Filipi, Z.S., Guralp, O., and D.N. Assanis, "Method for Mid-Load Operation of Auto-Ignition Combustion," Patent No. 7,128,062 B2, granted 10/31/2006.

Kuo, T.W., Najt, P., Eng, J.A., Rask, R.B., Guralp, O., Hoffman, M., Filipi, Z.S., and D.N. Assanis, "Method and Apparatus to Determine Magnitude of Combustion Chamber Deposits," Patent No. 7,367,319, granted 12/31/2007.

Najt, P., Kuo, T.W., Rask, R., Babajimopoulos, A., Filipi, Z.S.., Lavoie, G., and D. N. Assanis, "Hybrid Powertrain System Using Free Piston Linear Alternator Engines," Utility patent application, US serial no. 12/504,502, filed July 16, 2009.

Scott T. McBroom, P.E.

1915 Great Ridge St.
San Antonio, TX 78248
(210) 240-7123 (m)
(210) 492-4116 (h)
Email: scott.mcbroom@sbcglobal.net

OBJECTIVE

To obtain a management position within an innovative/entrepreneurial engineering company.

PROFESSIONAL SUMMARY

Experience with successfully managing all aspects of an advanced vehicle powertrain research and development activity. I have 7 years management experience and a total 17 years in vehicle research development. Responsibilities have included; personnel, cash flow, marketing, engineering, contracting, strategic planning, client relations, proposal writing, technical writing, presentations and significant travel. I believe my experience has been equivalent to founding and managing a small research and development business, which I lead from an initial staffing of 5 to 14 in 4 years.

EXPERIENCE

Southwest Research Institute – Manager of Advanced Vehicle Technology (**www.avt.swri.org**), San Antonio, TX, May 1998 - present

- Manage a staff of 13 engineers (2 PhD's, 6 MS's and 5 BS's), with annual gross revenues averaging $2.7M with a client portfolio of US Gov, US commercial, and foreign commercial clients, and a technology portfolio that includes; test systems, hybrid electric vehicles, hybrid hydraulic vehicles, software development, fuel cell systems, automated manual transmissions and electrification of engine accessories.
- Spearheaded the development of a commercial-of-the-shelf software package to simulate vehicle performance and fuel economy (RAPTOR). RAPTOR is now licensed by DaimlerChrysler, U.S. Army, AND Technologies, FAW Corporation and Denso. (www.raptor.swri.org)

Southwest Research Institute – Senior Research Engineer, San Antonio, TX, 1996 - 1998

- Developed software simulation tools to model vehicle performance, emissions and fuel economy for the Partnership for a New Generation Vehicle's (PNGV) 80-mpg car. Sponsored by Ford, GM and Chrysler.
- Powertrain Systems Analysis for the U.S. Army National Automotive Center's Future Truck program to improve the efficiency, safety and emissions of trucks in the US.

Southwest Research Institute – Research Engineer, San Antonio, TX, 1991 - 1996

- Conducted evaluation, simulation, design, and integration of electric, hybrid-electric, and solar-powered vehicles.
- Championed an internal research project for modeling the performance, emissions, and efficiency of conventional, hybrid and electric vehicles, which has since led to over $9M of client funded simulation projects.

Southwest Research Institute –Engineer, San Antonio, TX, 1988 - 1991

- Developed a retractable, compressible fluid, suspension system for an amphibious military vehicle.
- Designed and developed a regenerative active suspension system for a tour bus
- Reduced to practice a patented pump/motor for regenerative active suspension systems.
- Performed stability testing and failure analysis of an electro-hydraulic control valves.
- Designed and tested an air cycle refrigeration system.

Scott T. McBroom, P.E.

EDUCATION

Bachelor of Science in Mechanical Engineering, May 1988
The University of Maryland, College Park, Maryland

Master of Science in Mechanical Engineering, May 1998
The University of Texas at San Antonio, San Antonio, Texas

SKILLS

MATLAB/SimuLINK, Microsoft Office, Fluent in French, Cost Point, Project Management, Proposal Writing, Personnel Management, Public Speaking

ACTIVITIES & AWARDS

Professional

- Recognized by the San Antonio Business Journal as one of the top 40 individuals under 40 yrs old in the San Antonio business community - 2004
- Society of Automotive Engineers Outstanding Younger Member – South Texas Section 1994-95
- R & D Magazine 2004 R&D 100 Award for RAPTOR software (for the 100 most significant innovations)
- DOE/GM/EDS Sunrayce (Solar Car Race) – Chief Mechanical Inspector '95,'97 and '99

Personal

- Alamo Heights United Methodist Church (Production Team, Hospitality Team, Fishing Under the Bridge Team, and Alpha)
- Bonneville Salt Flats Racing Association – Land Speed Record for Electric Vehicles Under 500kg (101.3 mph) – (1994)
- Fourth place out of 16 in the first Solar and Electric 500 at Phoenix International Raceway and first place for hybrid electrics the second year. (1991)
- Completed the San Antonio, Austin and Columbus Marathons
- NEISD – Mentor for High School Students Interested in Engineering Careers

Professional Affiliations

Society of Automotive Engineers (member since 1986, Past Chair South Texas Section)
Registered Professional Engineer, State of Texas

Professional Development

Lean Six Sigma
Family Medical Leave Act Overview
Government Property Administration
Supervisory Management: Managing A Drug-Free Workplace
Time Management
Sexual Harassment Prevention And Resolution
Coaching For Improved Performance
SwRI Manager Support Briefings
Care-Employee Assistance Program
Fundamental Skills Of Managing People
Establishing Performance Expectations
Fundamental Skills Of Communicating With People
Getting Employee Commitment To The Plan
Project Financial Management Methods
Topics In Statistics 6: Methodologies For Fitting A Curve To Data
Successful Cost Estimating Methods
Statistical Design Of Industrial Experiments
Proposal Preparation
Undergraduate Mathematics Review : Partial Differential Eqn's
Research Program Development
State Variable Modeling Of Linear Systems

Publications

"The 1989 Formula SAE Student Design Competition," with L. Bendele, E. Bass, Society of Automotive Engineers, International Congress and Exposition, SAE Paper 900840, Detroit, MI, February 1990.

"System Tradeoffs - Design of Hybrid Electric Vehicles," with D. Mairet, J. Buckingham, E. Bass, ESD Technology, November 1994.

"PNGV Goal 3 Systems Analysis Toolkit," with K. Hardy, A. Sabharwal, Partnership for a New Generation of Vehicles Simulation Technology Design Team, August 1996.

"Analysis and Design of a Propane Gas/Electric Parallel Hybrid Vehicle," Masters Thesis for College of Sciences and Engineering, University of Texas at San Antonio, December 1998.

"Analysis for a Four-Wheel Propane-Electric Parallel Hybrid Vehicle," Society of Automotive Engineers, Future Transportation Technology Conference, SAE Paper No. 1999-01-2907, Costa Mesa, CA, August 1999.

"Modeling Future Automobiles: The Role of Industry and Government," co-authored with Larry Turner, Robert Larsen, Michael Duoba, Ashok Nedungadi, and Keith Wipke. COMPEL: The International Journal for Computation and Mathematics in Electrical and Electronic Engineering Volume 19, No. 4, 2000, Pp. 1036-1044.

"Class 2B – Light Duty Trucks and the 21st Century Truck Initiative," Clean SUV and Light Truck SAE TOPTEC, Dearborn, MI, June 2000.

"The 21st Century Truck – Comparing Various Efficiencies and Emissions Using Simulation-Based Parametric Analysis," Presented at Hybrid Vehicles 2000, Windsor, Canada, September 2000.

"A Parallel Hybrid System for Class IV Truck," presented at EnV 2001, sponsored by Engineering Society of Detroit in Detroit, MI, June 2001.

"Hybrid Power Trains for Future Tactical Wheeled Vehicles," Presented at Hybrid Electric Truck Users Forum (H-TUF), sponsored by WestStart in Indianapolis, IN, January 2002.

"Hybrid Technology Overview," Presented at Hybrid Electric Truck Users Forum (H-TUF), sponsored by WestStart in Indianapolis, IN, January 2002.

"A New Approach to Improving Fuel Economy and Performance Prediction Through coupled Thermal Systems Simulation," 2002 SAE Congress Paper No. 2002-01-1208, Presented at SAE 2002 Word Congress & Exhibition, March 2002, Co-Authors Joe Steiber and Angela Trader of SwRI, Alan Berry and Martin Blissett of Flowmaster International Ltd.

"Roadmap for Hybridization of Military Tactical Vehicles: How Can We Get There?", Presented at International Truck and Bus Meeting and Exhibition in Detroit, MI on November 18-20, 2002. SAE Paper No. 2002-01-3048

"System Analysis of the Effects of Hybridization on the Family of Medium Tactical Vehicles," presented at Hybrid Truck Users Forum in San Antonio, Texas on October 2003.

"The Impact of Hybridization on Engine Life: A Qualitative Assessment", presented as an oral only paper at the 2005 SAE Powertrain and Lubrication Conference, San Antonio, TX October 2005.

CURRICULUM VITAE
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EDUCATION

Engineering Education

Ph.D. — Mechanical Engineering — 6/2005
The Ohio State University — Columbus, OH
Dissertation Title: "Modeling, Control, and Diagnosis of a Diesel Lean NO_x Trap Catalyst"

M.S. — Mechanical Engineering — 3/2001
The Ohio State University — Columbus, OH
Thesis Title: "A Novel Fuel-Operated Heater for Automotive Thermal Management"

B.S. — Mechanical Engineering — *Summa cum Laude* — 6/1999
Wright State University — Dayton, OH
Senior Design Project: "Aerodynamic Design and Simulation of a Wind-Turbine"

Academic Fellowships

Graduate Automotive Technology Education Program – Ph.D. Studies — Source: Dept. of Energy
- Awarded to select graduate students conducting research supporting DOE goals for transportation research

University Fellowship – M.S. Studies — Source: Ohio State University
- Awarded in a university-wide search to attract high-caliber graduate students

RESEARCH EXPERIENCE

Research Appointments

Research Scientist — 10/2008 to present
Ohio State University Center for Automotive Research, Columbus, OH
- Conduct research in the area of clean and efficient transportation, including emissions reduction, Diesel engines, alternative combustion, hydrogen generation, heavy fuel atomization, and advanced powertrains
- Directed and advised graduate students in this area of research

Senior Research Associate — 11/2005 to 9/2008
Ohio State University Center for Automotive Research, Columbus, OH
- Conducted research in the area of clean and efficient transportation
- Directed and advised graduate students in this area of research

Research Associate II — 2/2004 to 10/2005
Ohio State University Center for Automotive Research, Columbus,
- Conducted research in the area of clean and efficient transportation

Research Intern 6/2003 to 9/2003

Ford Scientific Research Labs, Dearborn, MI

- Conducted research on emissions reductions for gasoline hybrid-electric vehicles
- Three-month assignment resulted in three Ford invention disclosures and two U.S. patents

Research Funding

Projects as PI / Co-PI:

$1,800,000/3 years	Title: Systems Level Development for Engine Thermal Management Source: DOE via Chrysler subcontract	Start: 10/2010 Role: co-PI
$50,000/1 years	Title: Analysis of Secondary Powertrain Systems in HEVs Source: CAR Industrial Consortium	Start: 10/2010 Role: PI
$40,000/0.5 years	Title: Life Cycle Analysis of Landfill Derived Natural Gas Source: FirmGreen	Start: 4/2009 Role: PI
$144,500/3 year	Title: Fleet Studies of Plug-In Electric Hybrid Vehicles Source: SMART@CAR Consortium	Start: 1/2009 Role: PI
$2,000,000/3 years[1]	Title: EcoCAR Challenge Hybrid Electric Vehicle Project Source: US Department of Energy and numerous other sponsors	Start: 6/2008 Role: Co-PI
$943,108/4 years	Title: Coordinated Diesel Engine and Aftertreatment Control Source: Cummins	Start: 4/2008 Role: PI
$724,531/3 years	Title: Hierarchical Approach to Engine Modeling Source: General Motors	Start: 4/2007 Role: Co-PI
$234,760/2 years	Title: Soot Filter Regeneration though External Heat Addition Source: Tenneco Automotive	Start: 11/2005 Role: Co-PI
$673,550/3 years	Title: On-Board Fuel Reformation for Diesel Aftertreatment Source: Tenneco Automotive	Start: 11/2005 Role: Co-PI

Projects with Major Research Role (not co-PI):

$940,863/4 years	Title: Next Generation Charge Estimation for IC Engines Source: General Motors	Start: 7/2004 Role: Researcher
$1,327,954/5 years	Title: Next Generation AFR Control for IC Engines Source: General Motors	Start: 7/2004 Role: Researcher

[1] This is the estimated cost of the research conducted under this problem if funded from an external sponsor. This project is heavily leveraged by the Department of Energy, General Motors, Ohio State University, and a number of other sponsors through in-kind contributions as well as direct funding and fellowships.

TEACHING EXPERIENCE

Instructional Appointments

Adjunct Assistant Professor 7/2009 to present
Ohio State University Department of Mechanical Engineering, Columbus, OH

- Granted in recognition of significant educational service to the Mechanical Engineering Department
- Service includes one-on-one student advising, student project advising, and supervision of undergraduate research

Instructor 4/2007 to present
Ohio State University Department of Mechanical Engineering, Columbus, OH

- Sole instructor of record for two applied thermal and fluids courses on internal combustion engines

Course Development

ME 631 - Powertrain Laboratory (3 CR) 1/2009
Ohio State University Department of Mechanical Engineering, Columbus, OH

- Developed course material for two quarter hours of classroom lecture which reinforced lab work
- Developed eight new lab experiments based on in-depth knowledge of the automotive industry
- Facilitated donation of a gasoline engine from General Motors and a Diesel engine from Cummins, both with a calibration system to provide students access to cutting-edge equipment

ME 730 - Internal Combustion Engine Modeling (3 CR) 4/2007
Ohio State University Department of Mechanical Engineering, Columbus, OH

- Developed all new lecture material to bring in personnel research experience
- Developed new homework assignments to better engage students by building a fully functioning engine model in stages of greater fidelity and complexity
- Facilitated the donation of industry-standard engine simulation software for use by students
- Developed capstone project which allowed students to become engaged in a topic of interest

Seminar - Alternative Fuels Short Course 1/2007
Ohio State University Center for Automotive Research Distance Education Program

- Developed 10 hours of lecture and lecture notes for industrial distance education program
- Provided case studies of alternative-fueled vehicles to reinforce concepts for the industry audience

Teaching Experience

ME 631 – Powertrain Laboratory (3 CR) Overall Teaching Rating: 5.0/5.0	Sole Instructor of Record Class Size: 16	1/2011
ME 631 – Powertrain Laboratory (3 CR) Overall Teaching Rating: 5.0/5.0	Sole Instructor of Record Class Size: 15	1/2010
ME 730 - Internal Combustion Engine Modeling (3 CR) Overall Teaching Rating: 4.4/5.0	Sole Instructor of Record Class Size: 7	4/2009
ME 631 – Powertrain Laboratory (3 CR) Overall Teaching Rating: 4.8/5.0	Sole Instructor of Record Class Size: 12	1/2009
ME 730 - Internal Combustion Engine Modeling (3 CR) Overall Teaching Rating: 4.5/5.0	Sole Instructor of Record Class Size: 8	4/2007

Academic Advising

Since 2005, Dr. Midlam-Mohler has become increasingly involved in student advising. He has served in an advisory or supervisory capacity to the following students at the M.S. and Ph.D. level:

Degree	Student	Role	Graduation Date or Expected Graduation Date
Ph.D.	Quiming Gong	Research Supervisor	2012
Vis. Scholar	Bernhard Grimm	Research Supervisor	2010
M.S.	John Davis	Co-Advisor	2011
Ph.D.	Jason Meyer	Research Supervisor	2011
Honors B.S.	Katherine Bovee	Acting Advisor	2010
Honors B.S.	John Davis	Acting Advisor	2010
Honors B.S.	Ryan Everett	Acting Advisor	2010
Ph.D.	Kenny Follen	Research Supervisor	2010
M.S.	Beth Bezaire	Acting Advisor	2010
M.S.	Brad Cooley	Acting Advisor	2010
M.S.	Chris Hoops	Acting Advisor	2010
M.S.	Ming Fang	Acting Advisor	2009
Honors B.S.	Chris Hoops	Acting Advisor	2009
M.S.	Rajaram Maringanti	Acting Advisor	2009
M.S.	Joshua Supplee	Acting Advisor	2009
Vis. Scholar	Adalbert Wolany	Supervisor	2009
Ph.D.	Sai Rajagopalan	Committee Member	2009
Ph.D.	Sergio Hernandez	Acting co-advisor	2008
Vis. Scholar	Andrea Pezzini	Supervisor	2008
Vis. Scholar	Patrick Rebechi	Supervisor	2008
Honors B.S.	Rhisee Bhatt	Acting co-advisor	2007
Vis. Scholar	Simone Bernasconi	Supervisor	2007
M.S.	Josh Cowgill	Acting co-advisor	2007
M.S.	Kenny Follen	Acting co-advisor	2007
M.S.	Courtney Coburn	Acting Advisor	2006
M.S.	Adam Vosz	Acting Advisor	2006
M.S.	Eric Snyder	Acting co-advisor	2005

Undergraduate Student Research Assistants:

Dr. Midlam-Mohler has supervised the following students on research outside of a formal degree program:

Degree	Student	Role	Year
B.S.	Abbey Underwood	Supervisor	2010
B.S.	Sarah Jadwin	Supervisor	2010
B.S.	Andrew Arnold	Supervisor	2009-2010
B.S.	John Macauley	Supervisor	2009-10
B.S.	Alixandra Keil	Supervisor	2009-10
B.S.	Jennifer Loy	Supervisor	2009-10

B.S.	Sean Ewing	Supervisor	2009
B.S.	David Griffin	Supervisor	2009
B.S.	Ross Wang	Supervisor	2009
B.S.	Orlando Inoa	Supervisor	2008-09
B.S.	Al Godfrey	Supervisor	2008-09
B.S.	John Lutz	Supervisor	2008
B.S.	Konrad Svzed	Supervisor	2008
B.S.	Joshua Supplee	Supervisor	2007

Mentor for Local High School Students

Dr. Midlam-Mohler has mentored seven local high school students for ~30 hours of activity per student since 2007.

Student Organization Advising

EcoCAR Challenge Hybrid Electric Vehicle Team 6/2008 - present
Ohio State University

- Co-advise 40 member (~80% undergraduate) student design project team competing in U.S. Department of Energy sponsored vehicle competition
- Oversee day-to-day operation of team as they model, design, build, and test a hybrid electric SUV
- Team won 1st place in first year, 4th place in second year
- Nominated by team for "NSF Advisor of the Year Award"

Challenge-X Hybrid Electric Vehicle Team 8/2006 – 6/2008
Ohio State University

- Co-advised primarily undergraduate team competing in Department of Energy Sponsored advanced technology vehicle completion
- Over the course of the four year competition from 2004 – 2008, OSU placed 3rd, 4th, 4th, and 3rd respectively in the premier advanced technology vehicle competition

PROFESSIONAL SERVICE

Professional Service

EPA GEM Model Reviewer, Columbus, OH
Peer Reviewer 12/2011

- Conducted peer review of a heavy-duty truck model developed by the U.S. EPA used for predicting fuel economy and green house gas emissions.

Clean Fuels Ohio, Columbus, OH 9/2009 to present
Member of the Board of Directors

- Elected to Board of Directors of Clean Fuels Ohio, a non-profit committed to cleaner transportation fuels

State of Indiana 4/2009
Proposal Reviewer

- Reviewed multi-million dollar proposal for Indiana grant program in area of internal combustion engines

Natural Gas Fleet Stakeholders Meeting, Grove City, OH 11/2008
Panel Member

- Served as panel technical expert on alternative vehicular fuels
- Meeting attended by designees' from the Governor's office and from both of Ohio's U.S. Senators' staff

McMaster Fuel Ltd., Perrysburg, OH 9/2006 to 1/2007
Independent Consultant

- Provided analysis of a hydrogen production technique against other methods of hydrogen production
- Provided analysis of these techniques for emissions reduction
- Assisted McMaster Fuel Ltd. in making strategic decisions regarding their technology

Publication Reviewer Continuous

- Review numerous publications for conferences and journal submission of ASME, SAE, IEEE, *etc.*

PUBLICATIONS

Scholarly Publications

Journal Articles:

1. Gong, Q. (supervised by SMM); Midlam-Mohler, S.; Marano, V. ; Rizzoni, G. ; "Statistical Analysis for PHEV Virtual Fleet Study", International Journal of Vehicle Design (IJVD). *Accepted but undergoing revisions.*
2. Meyer, J. (supervised by SMM); Midlam-Mohler, S.; Yurkoich, S. (colleague); "In-cylinder Oxygen Concentration Estimation for Diesel Engines Via Transport Delay", American Control Conference 2011; *Accepted but undergoing revisions.*
3. M. Canova, S. Midlam-Mohler, P. Pisu, A. Soliman, "Model-Based Fault Detection and Isolation for a Diesel Lean NOx Trap Aftertreatment System," Control Engineering Practice, November 2009.
4. M. Canova, S. Midlam-Mohler, Y. Guezennec, G. Rizzoni, "Mean Value Modeling and Analysis of HCCI Diesel Engines with External Mixture Formation," ASME Journal of Dynamic Systems, Measurement and Control, Vol. 131, No. 11, 2009.
5. M. Canova, S. Midlam-Mohler, Y. Guezennec, G. Rizzoni, "Theoretical and Experimental Investigation on Diesel HCCI Combustion with External Mixture Preparation," International Journal of Vehicle Dynamics, Volume 44, Nos 1-2, 2007.
6. N. Szabo, C. Lee, J. Trimboli1, O. Figueroa, R. Ramamoorthy, S. Midlam-Mohler, A. Soliman, H. Verweij, P. Dutta and S. Akbar, "Ceramic-Based Chemical Sensors, Probes and Field-Tests in Automobile Engines," Journal of Materials Science, November, 2003.

Conference Papers:

1. Gong, Q.; Tulpule, P.,Midlam-Mohler, S.; Marano, V.; Rizzoni, G.; "The Role of ITS in PHEV Performance Improvement", American Control Conference (ACC) 2011. *Accepted but undergoing revisions.*
2. Gong, Q. ; Midlam-Mohler, S.; Marano, V.; Rizzoni, G.; "An Iterative Markov Chain Approach for Generating Vehicle Drive Cycles", Accepted by SAE World Congress 2011. *Out for final review.*
3. Cooley, B; Vezza, D.; Midlam-Mohler, S.; Rizzoni, G.; "Model Based Engine Control Development and Hardware-in-the-Loop Testing for the EcoCAR Advanced Vehicle Competition", Accepted by SAE World Congress 2011. *Out for final review.*
4. K. Follen, M. Canova, S. Midlam-Mohler, Y. Guezennec, G. Rizzoni, B. Lee, G. Matthews, "A High Fidelity Lumped-Parameter Engine Model for Powertrain Control Design and Validation." In: ASME Dynamic Systems and Control Conference. Cambridge, MA, United States.
5. Qi. Gong, S. Midlam-Mohler, V. Marano, G. Rizzoni, Y. Guezennec, "Statistical analysis based PHEV fleet data study", 2010 IEEE Vehicle Power and Propulsion Conference, September, 2010.
6. Kerem Bayar, Beth Bezaire, Brad Cooley, John Kruckenberg, Eric Schact, Shawn Midlam-Mohler, Giorgio Rizzoni, "Design of an Extended-Range Electric Vehicle for the EcoCAR Challenge", ASME 2010 International Design Engineering Technical Conference, August, 2010.
7. J. Meyer, S. Yurkovich, S. Midlam-Mohler, "Architectures for Phase Variation Compensation in AFR Control," 2010 American Controls Conference, June, 2010.

8. R. Maringanti, S. Midlam-Mohler, M. Fang, F. Chiara, M. Canova, "Set-Point Generation using Kernel-Based Methods for Closed-Loop Combustion Control of a CIDI Engine," ASME DSCC2009, September, 2009.
9. J. Meyer, S. Rajagopalan, S. Midlam-Mohler, Y. Guezennec, S. Yurkovich, "Application of an Exhaust Geometry Based Delay Prediction Modal to an Internal Combustion Engine," ASME DSCC2009, September, 2009.
10. M. Fang, S. Midlam-Mohler, R. Maringanti, F. Chiara, M. Canova, "Optimal Performance of Cylinder-by-Cylinder and Fuel Bank Controllers for a CIDI Engine," ASME DSCC2009, September, 2009.
11. S. Midlam-Mohler, E. Marano, S. Ewing, D. Ortiz, G. Rizzoni, "PHEV Fleet Data Collection and Analysis," IEEE VPPC09, September 2009.
12. L. Headings, G. Washington, S. Midlam-Mohler, J. Heremans, "Thermoelectric Power Generation for Hybrid-Electric Vehicle Auxiliary Power," Proc. SPIE Int. Conference on Smart Structures and Materials, 2009, Vol. 7290, No. 13.
13. M. Canova, S. Midlam-Mohler, G. Rizzoni, F. Steimle, D. Boland, M. Bargende, "A Simulation Study of an E85 Engine APU for a Series Hybrid Electric Vehicle," 9th Stuttgart International Symposium on Automotive and Engine Technology, Stuttgart, Germany, 2009.
14. S. Rajagopalan, S. Midlam-Mohler, S. Yurkovich, Y. Guezennec, K. Dudek, "Control Oriented Modeling of a Three Way Catalyst Coupled with Oxygen Sensors," ASME Dynamic System and Controls Conference, Ann Arbor, MI, 2008.
15. L. Headings, S. Midlam-Mohler, G. Washington, and J. P. Heremans, "High Temperature Thermoelectric Auxiliary Power Unit for Automotive Applications," ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems, 2008, Paper #610.
16. K. Koprubasi, A. Pezzini, B. Bezaire, R. Cooley, P. Tulpule, G. Rizzoni, Y. Guezennec, S. Midlam-Mohler, "Application of Model-Based Design Techniques for the Control Development and Optimization of a Hybrid-Electric Vehicle", SAE World Congress 2009, Detroit, MI.
17. K. Sevel, M. Arnett, K. Koprubasi, C. Coburn, M. Shakiba-Heref, K. Bayar, G. Rizzoni, Y. Guezennec, S. Midlam-Mohler, "Cleaner Diesel Using Model-Based Design and Advanced Aftertreatment," SAE 2008-01-0868, 2008 International Congress, Detroit, MI, April 2008.
18. K. Dudek, B. Montello, J. Meyer, S. Midlam-Mohler, Y. Guezennec, and S. Yurkovich, "Rapid Engine Calibration for Volumetric Efficiency and Residuals by Virtual Engine Mapping," International Congress on Virtual Power Train Creation 2007, Munich, Germany, October 24-25, 2007.
19. M. Canova, S. Midlam-Mohler, Y. Guezennec, A. Soliman, and G. Rizzoni, "Control-Oriented Modeling of NOx Aftertreatment Systems," SAE ICE'07 Conference, Capri, Italy, September 2007.
20. M. Canova, F. Chiara, J. Cowgill, S. Midlam-Mohler, Y. Guezennec, G. Rizzoni, "Experimental Characterization of Mixed-Mode HCCI/DI Combustion on a Common Rail Diesel Engine," 8th International Conference on Engines for Automobile (ICE2007), Capri, Italy.
21. M. Canova, F. Chiara, M. Flory, S. Midlam-Mohler, Y. Guezennec, G. Rizzoni, "Experimental Characterization of Mixed Mode HCCI/DI Combustion on a Common Rail Diesel Engine," submitted to SAE ICE'07 Conference, Capri, Italy, September 2007.
22. M. Canova, M. Flory, Y. Guezennec, S. Midlam-Mohler, G. Rizzoni, and F. Chiara, "Dynamics and Control of DI and HCCI Combustion in a multi-cylinder Diesel engine," Paper 44, submitted to 5th IFAC Symposium on Advances in Automotive Control, Pajaro Dunes/Seascape, CA, August 2007.
23. A. Vosz, S. Midlam-Mohler, and Y. Guezennec, "Experimental Investigation of Switching Oxygen Sensor Behavior Due to Exhaust Gas Effects," Proc. of IMECE '06, Paper IMECE 2006-14915, Chicago, IL, November 2006.
24. S. Midlam-Mohler and Y. Guezennec, "A Temperature-Based Technique for Temporally and Spatially Resolved Lean NOx Trap Catalyst NOx Measurements," Proc. of IMECE '06, Paper IMECE 2006-14887, Chicago, IL, November 2006.
25. M. Canova, S. Midlam-Mohler, Y. Guezennec, G. Rizzoni, L. Garzarella, M. Ghisolfi, and F. Chiara, "Experimental Validation for Control-Oriented Modeling of Multi-Cylinder HCCI Diesel Engines," Proc. of IMECE '06, Paper IMECE 2006-14110, Chicago, IL, November 2006.
26. A. Soliman, S. Midlam-Mohler, Z. Zou, Y. Guezennec, and G. Rizzoni, "Modeling and Diagnostics of NOx Aftertreatment Systems," Proc. FISITA '06, Yokohama, Japan, October 2006.
27. Z. Zou, S. Midlam-Mohler, R. Annamalai, Y. Guezennec, V. Subramaniam, "Literature Survey of On-Board Hydrogen Generation Methods for Diesel Powertrains," Global Powertrain Conference, Novi, MI, Not Peer Reviewed, September 2006.

28. K. Follen, S. Midlam-Mohler, Y. Guezennec, "Diesel Particulate Filter Regeneration with an External Burner," Global Powertrain Conference, Novi, MI, Not Peer Reviewed, September 2006.
29. S. Midlam-Mohler and Y. Guezennec, "Regeneration Control for a Bypass-Regeneration Lean NOx Trap System," American Control Conference '06, Minneapolis, MN, Invited paper, June 2006.
30. A. Soliman, I. Choi, S. Midlam-Mohler, Y. Guezennec, G. Rizzoni, "Modeling and Diagnostics Of NOx After-Treatment Systems," SAE Paper 2006-05-0208, 2006 International Congress, Detroit, MI, April 2006.
31. S. Midlam-Mohler and Y. Guezennec, "Design, Modeling and Validation of a Flame Reformer for LNT External By-Pass Regeneration," SAE Paper 2006-01-1367, 2006 SAE International Congress, Detroit, MI, April 2006.
32. S. Midlam-Mohler, and Y. Guezennec, "Modeling of a Partial Flow Diesel, Lean NOx Trap System," Proc. of IMECE '05, Paper IMECE 2005-80834, Orlando, FL, November 2005.
33. M. Canova, L. Garzarella, M. Ghisolfi, S. Midlam-Mohler, Y. Guezennec, and G. Rizzoni, "A Control-Oriented Mean-Value Model of HCCI Diesel Engines with External Mixture Formation," Proc. of IMECE '05, Paper IMECE 2005-79571, Orlando, FL, November 2005.
34. A. Soliman, P. Jackson, S. Midlam-Mohler, Y. Guezennec, and G. Rizzoni, "Diagnosis of a NOx Aftertreatment System," ICE 2005 7th International Conference on Engines for Automobiles, Capri, Italy, September 2005.
35. M. Canova, L. Garzarella, M. Ghisolfi, S. Midlam-Mohler, Y. Guezennec, and G. Rizzoni, "A Mean-Value Model of a Turbo-Charged HCCI Diesel Engine with External Mixture Formation," ICE 2005 7th International Conference on Engines for Automobiles, Capri, Italy, September 2005.
36. M. Canova, R. Garcin, S. Midlam-Mohler, Y. Guezennec, and G. Rizzoni, "A Control-Oriented Model of Combustion Process in HCCI Diesel Engines," American Control Conference '05, Portland, OR, June 2005.
37. C. Musardo, B. Staccia, S. Midlam-Mohler, Y. Guezennec, and G. Rizzoni, "Supervisory Control for NOX Reduction of an HEV with a Mixed-Mode HCCI/CIDI Engine," American Control Conference '05, Portland, OR, June 2005.
38. M. Canova, A. Vosz, D. Dumbauld, R. Garcin, S. Midlam-Mohler, Y. Guezennec, and G. Rizzoni, "Model and Experiments of Diesel Fuel HCCI Combustion with External Mixture Formation," 6th Stuttgart International Symposium on Motor Vehicles and Combustion Engines, Stuttgart, Germany, Not peer reviewed, February 2005.
39. S. Midlam-Mohler, S. Haas, Y. Guezennec, M. Bargende, G. Rizzoni, S. Haas, and H. Berner, "Mixed-Mode Diesel HCCI/DI with External Mixture Preparation," Paper F2004V258, Proc. FISITA '04 World Congress, Barcelona, Spain, May 2004.
40. Y. Guezennec, C. Musardo, B. Staccia, S. Midlam-Mohler, E. Calo, P. Pisu, and G. Rizzoni, "Supervisory Control for NOx Reduction of an HEV with a Mixed-Mode HCCI/DI Engine," Paper F2004F233, Proc. FISITA '04 World Congress, Barcelona, Spain, May 2004.
41. M. Gilstrap, G. Anceau, C. Hubert, M. Keener, S. Midlam-Mohler, K. Stockmeier, J-M Vespasien, Y. Guezennec, F. Ohlemacher, and G. Rizzoni, "The 2002 Ohio State University FutureTruck – the BuckHybrid002," 2003 SAE International Congress and Exposition, Detroit, MI, March 2003.
42. Y. Guezennec, S. Midlam-Mohler, M. Tateno, and M, Hopka, "A 2-Stage Approach to Diesel Emission Management in Diesel Hybrid Electric Vehicles," Proc. 2002 IFAC Meeting, Barcelona, Spain, July 2002.
43. M. Hopka, A. Brahma, Q. Ma, S. Midlam-Mohler, G. Paganelli, Y. Guezennec, and G. Rizzoni, "Design, Development and Performance of Buckeyebrid: The Ohio State Hybrid Electric FutureTruck 2001," SAE SP-1701, Not peer reviewed, March 2002.

Scholarly Presentations Independent of Paper Publications:

1. S. Midlam-Mohler and Y. Guezennec, "Lean NOx Trap Modeling Based on Novel Measurement Techniques," CLEERS Conference Workshop 3, Not peer reviewed, May 4, 2006.
2. S. Midlam-Mohler, and Y. Guezennec, "Design, Modeling and Validation of a Flame Reformer for LNT External By-Pass Regeneration," 2005 DEER Conference, Chicago, IL, Not peer reviewed, August 2005.
3. M. Canova, S. Midlam-Mohler, Y. Guezennec, and G. Rizzoni, "Control-Oriented Modeling of HCCI Combustion," 2005 DEER Conference, Chicago, IL, Not peer reviewed, August 2005.
4. S. Midlam-Mohler and Y. Guezennec, 2004 DEER Conference, San Diego, CA, Not peer reviewed, August 2004.
5. S. Midlam-Mohler, Y. Guezennec, G. Rizzoni, M. Bargende, and S. Haas, "Mixed-Mode Diesel HCCI with External Mixture Preparation," 2003 DEER Conference, Newport, R. I., Not peer reviewed, August 2003.

6. S. Midlam-Mohler, Y. Guezennec, “An Active, Thermo-Chemically Managed Diesel NOx After-Treatment System,” CLEERS Conference Workshop 2, Not peer reviewed, October 11, 2001.

Intellectual Property Activity

Issued Patents:

1. S. Midlam-Mohler, B. Masterson, "System System for Controlling NOx Emissions During Restarts of Hybrid and Conventional Vehicles,” U.S. Patent 7,257,493, awarded 3/21/07.
2. S. Midlam-Mohler, "System and Method for Reducing NOx Emissions after Fuel Cut-Off Events,” U.S. Patent 7,051,514, awarded 5/30/06.

Patent Applications:

1. S. Liu, K. Dudek, S. Rajagopalan, S. Yurkovich, Y. Hu, Y. Guezennec, S. Midlam-Mohler, “Off-Line Calibration of Universal Tracking Air Fuel Ratio Regulators,” U.S. Patent Application 20090271093, 10/29/2009.
2. S. Rajagopalan, K. Dudek, S. Liu, S. Yurkovich, S. Midlam-Mohler, Y. Guezennec, Y. Hu, “Universal Tracking Air-Fuel Regulator for Internal Combustion Engines, U.S. Patent Application 20090266052, 10/29/2009.
3. K. Dudek, S. Rajagopalan, S. Yurkovich, Y. Guezennec, S. Midlam-Mohler, L. Avallone, I. Anilovich, “Air Fuel Ratio Control System for Internal Combustion Engines,” U.S. Patent Application 20090048766, 2/19/2009.
4. Y. Guezennec and S. Midlam-Mohler, Shawn, “Fuel Preparation System for Combustion Engines, Fuel Reformers and Engine Aftertreatment,” U. S. Patent Application 20040124259, 7/1/04
5. S. Midlam-Mohler and B. Masterson, "System and Methods for the Reduction of NOx Emissions after Fuel Cut-Off Events,” U.S. Patent application 20060021326, filed 2/2/03.
6. S. Midlam-Mohler and B. Masterson, "Strategy for Controlling NOx Emissions During Hot Restarts for Hybrid and Conventional Vehicles,” U.S. Patent Application 20060021330, filed 2/2/03.

Patent Applications in Preparation:

1. J. Meyer, S. Midlam-Mohler, K. Dudek, S. Yurkovich, Y. Guezennec, Topic: Engine emissions control, Status: submitted to patent office 9/09.
2. J. Meyer, S. Midlam-Mohler, K. Dudek, S. Yurkovich, Y. Guezennec, Topic: Engine emissions control, Status: submitted to patent office 9/09.
3. S. Midlam-Mohler, S. Rajagopalan, K. Dudek, S. Yurkovich, Y. Guezennec, Topic: Catalyst modeling for improved emissions control, Status: Patent application being prepared by outside counsel.

ROBERT F. SAWYER **BS, MS, MA, PhD, PE, NAE**

Dr. Sawyer studied at Stanford University in the Department of Mechanical Engineering (B.S. 1957, M.S. 1958). He served as a Rocket Test Engineer, Rocket Propulsion Research Engineer, and Chief of the Liquid Systems Analysis Section at the Air Force Rocket Propulsion Laboratory, Edwards AFB, California (1958-1961). His later graduate and doctoral degree work was at the Guggenheim Aerospace Propulsion Laboratories of the Department of Aerospace Sciences at Princeton University (M.A. 1963, Ph.D. 1966).

He joined the faculty of the Mechanical Engineering Department of the University of California at Berkeley as an assistant professor in 1966 and served through the rank of full professor (1991). He held a joint appointment as a Senior Faculty Scientist at the Lawrence Berkeley Laboratory. At Berkeley he was Vice Chairperson for Graduate Studies of the Department of Mechanical Engineering (1980-1983) and Chairperson of the Energy and Resources Group (1984-1988), an interdisciplinary graduate department treating energy, resource, and environmental policy. He was selected the first Class of 1935 Professor of Energy (1988). Visiting appointments included: Visiting Research Scientist at the Johns Hopkins University Applied Physics Laboratory (1971), Visiting Researcher at Imperial College (1978-1979), Visiting Professor at Hokkaido University (1984), Visiting Professor at the Toyohashi University of Technology (1984), Visiting Scientist at the Sandia National Laboratory Combustion Research Facility (1988-1989), and Honorary Research Fellow at University College London (1991).

Dr. Sawyer served on the President's Council on Environmental Quality Advisory Committee on Alternative Automotive Power Systems (1971-1976), headed the Technology Panel of the National Academy of Sciences Committee on Motor Vehicle Emissions (1973-1974), chaired the State of California ad hoc Committee on Atmospheric Carcinogens (1978-1979), chaired the National Academy of Sciences Committee on Diesel Engine Technology (1979-1982), served as a member of the National Research Council Committee on Army Basic Research (1987-1988), a member of the California Air Resources Board (1975-1976), a director of KVB, Inc. (1975-1978), a director of the Center for Emissions Research and Analysis (1991-1994), a member of the External Advisory Panel to the World Bank Mexico City Transport Air Quality Management Program (1992-1996), a Senior Policy Advisor to the Office of Air and Radiation of the U.S. Environmental Protection Agency (1994-1995), a member of the Distinguished Advisory Panel to the Joint Auto/Oil Air Quality Improvement Research Program (1988-1996), a member of the U.S. EPA Blue Ribbon Panel on MTBE, and a member of the National Research Council Committee to Review the MOBILE Model, the Committee on Congestion Mitigation and Air Quality (CMAQ), and the Committee on Light Duty Vehicle Fuel Economy. He chaired the Health Effects Institute Special Committee on Emerging Technologies. He chaired the Bay Area Air Quality Management District Advisory Council (2003) and was co-chair of the USEPA Mobile Sources Technical Advisory Sub-committee (1996-2003).

In 2005 Dr. Sawyer accepted the appointment by Governor Schwarzenegger to chair the California Air Resources Board, a position he held until 2007. This agency with 1200 employees and a budget of more than 750 million dollars oversees California's air quality and global warming programs. He was a member of the United Nations International Civil Aviation Organization Independent Experts Panel on Fuel Burn Reduction Technology (2009-2010). He is a member of the Advisory Committee to the College of Engineering Center for Environmental Research and Technology at the University of California at Riverside and of the Board of Advisors of the Institute of Transportation Studies at the University of California at Davis, and the International Advisory Board of the Center for Combustion Energy, Tsinghua University. He serves on the National Research Council Board on Environmental Science and Toxicology, the National Academy of Engineering/National Research Council Committee on Analysis of Causes of the Deepwater Horizon Explosion, Fire, and Oil Spill to Identify Measures to Prevent Similar Accidents in the Future, and the National Research Council Committee on Transition to Alternative Vehicles and Fuels. He serves on the USEPA Mobile Sources Technical Review Sub-committee and is a member of the International Council for Clean Transportation. He serves on the board of directors of the American Lung Association in California.

Dr. Sawyer served as President of the International Combustion Institute (1992-1996), is a Fellow of the Society of Automotive Engineers, Associate Fellow of the American Institute of Aeronautics and Astronautics, and a member of American Society of Mechanical Engineers and the American Association of University Professors. He is a Registered Professional Engineer (Mechanical Engineering and Fire Protection Engineering) in the State of California. He is a recipient of the Berkeley Citation and the Sechiro Honda Medal of the Society of Mechanical Engineers. He is listed in *Who's Who in America, American Men and Women of Science, Who's Who in Technology, Who's Who in Engineering, Who's Who in Science and Engineering,* and *Who's Who in the West.* Dr. Sawyer is a member of the National Academy of Engineering. He is a partner of Sawyer Associates, an engineering consulting business.

At Antelope Valley College (Lancaster, California) Dr. Sawyer was a part-time instructor of physics and mathematics (1959-1961). At the University of California at Berkeley, he taught undergraduate and graduate courses in combustion, propulsion, thermodynamics, energy conversion, engines, air pollution, and fire safety (1966-1991). As Professor of the Graduate School, the Class of 1935 Professor of Energy Emeritus, and Senior Research Engineer at the Lawrence Berkeley Laboratory (1991-2005) he conducted research and advised undergraduate and graduate research students in motor vehicle emissions and control, toxic waste incineration, and regulatory policy. He continued some teaching at Berkeley during this period including the undergraduate courses, "Energy and Society" and "The Automobile, Energy, and The Environment" and the graduate courses, "Interdisciplinary Energy Analysis" and "Critical Issues in Air Pollution for the 1990s." He is a Visiting Professor of Energy and Environment at University College London (1995-). He directed the University of California Study Abroad Center in London, England (2003-2005). Following his service in the California state government, he resumed his work at Berkeley where teaches the freshman seminar "The Science, Technology, Policy, and Politics of California Air Pollution." He is the author or co-author of more than 350 publications and the co-author of two books, *The Chemistry of Propellants* and *Combustion Sources of Air Pollution and Their Control*.

Dr. Sawyer was born in Santa Barbara, California in 1935. He served in the U.S. Air Force (active duty, 1958-1961), reaching the rank of captain (USAFRes). He lives in Oakland, California with his wife, Barbara Sawyer, who is a faculty member and past Chair of the Academic Senate at Diablo Valley College. Their daughters, Allison Shaffer, a finance analyst, and Lisa Sawyer, an architect, live in Davis, California.

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February 2011

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1. Academic Background

MSME	University of Michigan, Ann Arbor	Mechanical Engineering
BME	Rensselaer Polytechnic Institute	Mechanical Engineering

2. Professional Licenses/Certification

Registered Professional Engineer, State of Michigan

3. Relevant Professional Experience

Areas of Expertise:
- Engine research and development
- Emission control systems
- Powertrain electronic control systems
- Powertrain calibration
- Systems engineering

1994 – 2004 Chief Engineer and Technical Fellow
(Retired Oct 2004) Powertrain Systems Technology and Processes
(32+ years service) Ford Motor Company, Dearborn, MI

Responsible for development, application and certification of emission and powertrain control system technologies for all Ford Motor Company's North American vehicles.
- Developed technologies for emission control systems, powertrain control systems, OBD II (On-Board Diagnostic) systems and powertrain calibration procedures. Achieved U.S. EPA (Environmental Protection Agency) and CARB (California Air Resources Board) certifications for all 1993-2005 model year North American vehicles.
- Developed and implemented, in production, new technology catalyst systems for increasingly stringent emission standards with significant reductions in precious metal usage.
- Developed technologies for California LEV II (Low Emission Vehicle – 2nd Generation) and EPA SFTP (Supplemental Federal Test Procedure) regulations.
- Developed key low emission technologies for the engine, powertrain control system, exhaust emission and vapor emission control systems in the 2003 California SULEV (Super Ultra Low Emission Vehicle) Ford Focus, which was the first domestic production vehicle complying with the most stringent emission levels required by the California Air Resources Board.

- Developed the first analytical and laboratory based (engine and vehicle) automated powertrain calibration process with objective measures of driveability to replace the traditional on-the-road calibration process resulting in significant reductions in test vehicles and significant improvements in efficiency.
- Initiated production implementation of the first domestic application of a diesel particulate filter (DPF) with active regeneration.

Co-Chairman of the Ford Corporate Technical Specialist Committee which provided corporate overview in promoting deep technical expertise through the selection and appointment of technical specialists.

1992-1994 Assistant Chief Engineer
Powertrain Systems Engineering
Ford Motor Company, Dearborn, MI

Responsible for the development and certification of emission and powertrain control systems for all Ford Motor Company's North American vehicles.
- Developed and implemented, in production, the California LEV (Low Emission Vehicle) requirements featuring palladium-only catalysts and coordinated strategy for starting with reduced emissions (CSSRE).
- Developed and implemented OBD II, which was phased-in on all North American vehicles over the 1994-1996 model years.
- Developed and phased in the advanced EEC V electronic engine control system on all production vehicles over the 1994-1996 model years.
- Led the development and implementation of enhanced evaporative emission and running loss controls that were phased-in over the 1995-1999 model years.
- Led the establishment of systems engineering in the development of powertrain systems. Design specifications were developed for all powertrain sub-systems.

1990-1992 Executive Engineer/Manager
Powertrain Electronics (Containing 4 Departments)
Ford Motor Company, Dearborn, MI

Responsible for the development and production implementation of powertrain electronic control systems (hardware and software) for all of Ford Motor Company's North American vehicles.
- Developed production powertrain electronic control systems for all North American vehicles.
- Developed the technology for OBD II and the advanced EEC V electronic engine control system.
- Led the Powertrain Electronics Control Cooperation (PECC) program resulting in the application of Ford EEC V systems on 30% of Mazda vehicle lines by the 2000 model year.
- Initiated the development of Ford's next generation 32-bit powertrain electronic control system (PTEC) (implemented in the 1999 model year).

1987-1990 Manager
Advanced Powertrain Control Systems Department
Ford Motor Company, Dearborn, MI

Responsible for the development of powertrain control system technology for future applications.

- Developed the first Ford California ULEV (Ultra Low Emission Vehicle) emission control system. Major improvements in air/fuel ratio control were achieved using a UEGO (universal exhaust gas oxygen) sensor and a proportional control algorithm.
- Developed enhanced evaporative and running loss emission control concepts.
- Developed the first Ford traction control system using engine torque modulation combined with brake modulation.
- Developed the first Ford electronic throttle control (drive-by-wire) system for improved driveability (implemented in production for the 2003 model year).
- Developed engine torque modulation during shifting for imperceptible automatic transmission shifts.
- Initiated the requirements specification for a new 32-bit powertrain electronic control system (PTEC).

1978-1987 Manager
Engine Research Department
Research Staff
Ford Motor Company, Dearborn, MI

Responsible for the creation, identification and feasibility prove-out of advanced engine concepts for next generation vehicle applications.

- Developed the first Ford passenger car, direct-injection diesel that met current emission requirements and provided 10-15% fuel economy improvement vs. indirect injection diesel.
- Developed light-duty diesel electronic control systems that achieved significant reductions in emissions.
- Developed the first Ford adiabatic diesel engine with a ringless ceramic piston operating in a ceramic cylinder.
- Developed the concept and demonstrated the first Ford diesel particulate filter (DPF) with active regeneration that provided over 90% reduction in particulate emissions (scheduled for production in a Ford vehicle in 2007).

1974-1978 Supervisor, Development Section
Diesel Engine and Stratified Charge Engine Department
Ford Motor Company

Responsible for the research and development of low emission, fuel-efficient stratified charge engines (PROCO stratified charge, 3 valve CVCC (Compound Vortex Controlled Combustion), spark ignited-direct injection) and diesel engines.

1972-1974 Supervisor/Senior Research Engineer
Turbine Controls and Combustion Section
Ford Motor Company

Responsible for the research and development of low emission combustion systems for a high temperature, ceramic gas turbine engine.

- Developed the first successful premixed, pre-vaporized, variable geometry gas turbine combustion system that met the most stringent emission standards in the 1970's.

1967-1972 Research Engineer
General Motors Research Laboratory, Warren, MI

Responsible for the research and development of low emission combustion systems for gas turbine, Stirling and steam engines for potential automotive applications.

4. <u>Consulting</u>

2007-2008 Expert Witness for Orrick, Herrington and Sutcliffe, LLP

Expert witness for the plaintiff in a trade secret case involving diesel emission control systems (represented by Orrick, Herrington and Sutcliffe, LLP). Case was successfully settled after expert testimony. (May 2007 – December 2008)

2009 U.S. Environmental Protection Agency/ICF Consulting Group, Inc.

Evaluated the U.S. EPA's methodology for analyzing the manufacturing costs of vehicle powertrain and propulsion system technologies with low greenhouse gas emissions.

2009-Present Technical Advisory Board, Achates Power, Inc.

Technical advisor to Achates Power, Inc. for the development of unique technologies for new, fuel efficient, high power density engines.

2010 Expert Witness for Scott L. Baker, A Professional Law Corp.

Expert witness for the plaintiff in a case involving retrofit emission control systems (represented by Scott L. Baker). Case was successfully settled after expert testimony. (October – November 2010)

5. <u>Associated Experience</u>

1965-1966 1st and 2nd Lieutenant
U.S. Army

- 1965 Frankford Arsenal – Responsible for developing improvements in the save capability of high-speed aircraft emergency ejection seats using propellant actuated devices.
- 1966 Cam Ranh Bay, Vietnam – Assistant Adjutant, U.S. Army Depot

1967-1991 Lt. Col. and prior ranks
U.S. Army Reserve

Annual Training (Mobilization Designation Training)– Deputy Chief of Staff for Research, Development and Acquisition (DCSRDA), Department of the Army, Washington, DC

- Responsible for technical analysis of critical powerplant programs for the Army's mobility equipment

6. Professional Affiliations

Society of Automotive Engineering (SAE) – Fellow Member
American Society of Mechanical Engineers (ASME)– Fellow Member
Engineering Society of Detroit (ESD) – Member

7. Patents

Issued 29 U.S. patents and numerous foreign patents in the following areas:

- Low emission combustion systems
- Diesel particulate filters
- Adiabatic engine design
- Engine control systems
- OBD II monitor systems
- Traction control

8. Publications

Published 25 technical papers on powertrain research and development in SAE, IMechE, FISITA, ASME, API, NPRA (National Petroleum Refiners Association) and CRC.

9. Significant Awards

- Elected a member of the National Academy of Engineering (NAE), which is among the highest professional distinctions accorded to an engineer – For outstanding contributions in the implementation of low-emission technologies in the automotive industry (2011).
- Recognized as an innovator in the automotive industry by being appointed as one of the first Henry Ford Technical Fellows (1994) (technical ladder position equivalent to Engineering Director in Ford Motor Company).
- ASME Soichiro Honda Medal for technical achievements and leadership in every phase of automotive engineering, including 26 patents related to both gasoline and diesel engines (2007).

- SAE Edward N. Cole Award for Automotive Engineering Innovation – For outstanding creativity and achievement in the field of automotive engineering (2006).
- Honored by being invited to present the 2003 Soichiro Honda Lecture at the ASME Internal Combustion Engine Division Meeting (September, 2003). The lecture provided a comprehensive description of the technology incorporated in the first domestic SULEV vehicle.
- Honored by the Inventors Hall of Fame as a Distinguished Corporate Inventor (1997).
- Elected by ASME to Fellow Member Grade in recognition of outstanding accomplishments in engine combustion, efficiency and emissions research and development (2010).
- Elected by SAE to Fellow Member Grade in recognition of major technical contributions in the area of diesel engine research (1985).
- Honored with 5 SAE Arch T. Colwell Merit Awards for SAE technical publications.
- Selected as SAE Teetor Industrial Lecturer (1985-86 and 1986-87) and invited to present lecture at multiple universities.
- Received the prestigious Henry Ford Technology Award for development of regenerative diesel particulate filter systems (1986).
- Honored with the SAE Vincent Bendix Automotive Electronics Engineering Award (1983).

10. Professional Service

- Chair, ASME Soichiro Honda Medal Committee (2008-Present)
- Member of the 21st Century Truck Partnership-Phase 2 Study Committee of the National Research Council (2010 – Present)
- Past member of the 21st Century Truck Partnership Study Committee of the National Research Council (2007-2008)
- Past member of the Low Heat Rejection Engines Study Committee of the National Research Council (1985-1986)
- Past participant in Workshop for the National Research Council's Study on "Automotive Fuel Economy – How Far Should We Go?" (1991)
- Past member of the SAE Forum on Sustainable Development in Transportation to provide a technical response to President Clinton's initiative on future technology and the environment.
- Past member and chairman of the SAE Teetor Educational Awards Committee
- Past member of SAE ABET Relations Committee
- Past member of SAE Transaction Selection Committee for Advanced Powerplants and Emissions
- Past member of SAE Gas Turbine Committee (early 1970's)

Appendix C. Peer Reviewer Comments as Submitted, Round 1

Report Review on

"Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe"

Ricardo, Inc.

Dennis Assanis

SUMMARY COMMENTS

The objective of this reported study is to identify the relative impact of novel and advanced light-duty vehicle technologies on fuel economy and greenhouse gases in the 2020-2025 timeframe. The objective is pursued by comparing different "packages" of advanced powertrain technology through the application of a model-based vehicle simulation software in conjunction with experimental data and empirical rules. Vehicles comprising seven different platforms are considered. Representative vehicles from each platform are identified for relevance and for limited validation of the simulation predictions against measured acceleration and fuel consumption for a 2010 baseline case. In the spirit of improving the quality of the study and the report, the reviewer provides several general and detailed comments for consideration by the contracting agency and the authors of the report.

The report is intended to provide administrators, product planners and legislators a practical tool for assessing what is achievable, as well as insight into the complexity of the path forward to reach those advances that will be useful for productive discussions between EPA and the manufacturers. This path forward involves trade-offs among many design choices involving available, and soon-to-be-available advances in engine technologies, hybridization, transmissions and accessories. The current version of the simulation effort seems reasonably balanced in the attention paid to each of these areas. The range of improvements shown in the technologies considered and examples is encouraging.

Overall, the project attempts to undertake an analytical technology assessment study of significant scope. It does a fairly competent job at analyzing a select number of technologies and packages, mostly aimed at improving the gasoline IC engine, and to a less extent the diesel engine. It complements improvements on the engine side with synergistic developments on the transmissions, hybrids and accessories. The main shortcoming of the study is that the methodology relies extensively on proprietary and undisclosed data, as well as empirical rules, correlations and modifiers without citing published reference sources. Beyond the perceived lack of transparency, keeping up with new technologies or approaches will necessarily involve new versions of the program since the actual models of the technologies used are proprietary and the choice and range of parameters available to users is fixed and to some extent hidden. Due to these constraints, the simulation tool is limited in its ability to provide fundamental insight; this will require a more basic thermodynamic approach, perhaps best carried out by universities.

For the most part, the right technologies are being considered. However, certain promising technologies and fuel options for IC engine technologies (other than gasoline and diesel) that can make a significant contribution to the improvement of mpg and reduction of CO_2 emissions have not been considered, or even mentioned at all. Primary examples are advanced combustion technologies, such as high pressure, dilute burn, low temperature combustion (e.g., Homogeneous Charge Compression Ignition, Partially Premixed Compression Ignition, Spark-Assisted Compression Ignition), and closed-loop, in-cylinder pressure feedback. Some of these combustion technologies have the potential to improve fuel economy by up to 25%. Another significant assumption is that fuels used are equivalent to either 87 octane pump gasoline or 40 cetane pump diesel. However, advanced biofuels, particularly from cellulosic or lingo-cellulosic bio-refinery processes, which from the standpoint of a life cycle analysis have strong potential for reduction of CO_2 emissions, can have significantly different properties (including octane and cetane numbers) and combustion characteristics than the current fuels. Note that over 13 billion gallons of renewables were used in 2010, primarily from corn-ethanol and some biodiesel. According to the Renewable Fuel Standard, 36 billion gallons of renewables need to be used by 2022. Also, a joint study carried-out by Sandia and General Motors has shown that ninety billion gallons of ethanol (the energy equivalent of approximately 60 billion gallons of gasoline) can be produced in the US by year 2030 under an aggressive biofuels deployment schedule.

The report is lengthy at places, for instance in the description of technologies which users of the simulation software are likely to be already familiar with, while too laconic at other places, e.g. how the selected technologies were modeled in some detail. The draft can benefit from better balancing of its sections. There should also be more words summarizing the illustrative results (e.g., provide ranges of benefits), and assessing them critically (e.g., which technologies seem to incrementally or additively contribute the most), rather than just stating that the results are in Table 7.1 or in Appendix 3. A discussion of uncertainties present in the analysis should be presented so as to enable the reader to place the findings into proper perspective.

The characterization of the modeling methodology as objective and "scientific" suggests that the simulation is composed of rigorous, first-principle expressions for the various phenomena without using "correlations", "empirical formulas", and "phenomenological models". Are these conditions truly met? For instance, in many cases, steady-state dyno test data are the basis of an engine map featuring a certain technology. In other cases, available data were scaled based on empirical/proprietary factors and modifiers. The report should not characterize the study as "scientific" unless data uncertainty is discussed and shown in appropriate situations. For example, Table 7.1 presents comparisons between simulated and actual vehicle fuel economy performance. Given the various subjective assumptions involved in the analysis, the authors should comment whether the noticeable differences in certain cases are significant.

TECHNICAL COMMENTS

(1) **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Examples might include: engine technology selection, battery SOC swing, accessory load assumptions, etc. Please comment on any caveats or limitations that these inputs and parameters would affect the final results.

- The report describes a comprehensive set of engine and vehicle technologies for the prediction of GHG emissions and performance. However, the full range of inputs and parameters is not explicitly presented. It requires the reader to refer to the Data Visualization Tool figures to understand what exactly can be varied when querying the RSM. Even within the actual tool simulation environment, it is impossible to extract details on, or judge the basis for a number of critical inputs. In some occasions, the report mentions that published data have been used, but there are no references to the source. Baseline engine maps, torque converter maps and shifting maps, electric machine efficiency maps, and control strategies for hybrids, which have very direct effects on vehicle performance and emissions, should be presented in the report, at least in a limited format. Below are some examples of the types of inputs and parameters that would be helpful to include the following in the report:

(i) Any published fuel economy maps, or other related data, with actual numbers. For proprietary maps and data, a normalized representation would be useful, as well, without the actual bsfc values shown on the map.
(ii) Baseline maps used to represent turbomachinery, in actual or normalized form
(iii) The baseline vehicle cooling system and accessory schematic vs. cooling system and accessory load schematics of the future engines considered in the simulation
(iv) Details of EGR modeling parameters, such as maps showing percentage of EGR being used at various loads.
(v) Details of warm-up model parameters, such as ambient temperature; warm up friction correction; cold start fuel consumption correction factor; generation of heat rejection maps for various combinations in the simulation matrix

- The engine technology selection appears somewhat limited in terms of the selected combinations. For example, why is the Atkinson engine not boosted as well? Moreover, a variable valve actuation technology, as common and important as variable cam phasing, is not included. As already stated in the introductory comments, advanced combustion technologies, such as HCCI, are worth considering. More flexibility in the engine and vehicle parameters would also allow better understanding of the improvements obtained for individual technologies and possibly even show some potential synergies not currently identified.

- Alternative fuels are currently a key research topic and very important for future energy independence. Because usage of these fuels can have an impact on efficiency and emissions, the study would be enhanced if engine performance maps with various fuels were included.

(2) **Simulation methodology.** Please comment on the validity and applicability of the methodologies used in simulating these technologies with respect to the entire vehicle. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations. Does the model handle synergistic affects of applying various technologies together?

- The RSM approach is certainly a good way to provide quick access to wide range of results, but it has the limitation that a large number of assumptions have to be made ahead of time in order to determine the design space. Also, creating these encompassing RSM’s requires a significant amount of simulations, and all the results will not necessarily be of interest. If a more flexible model/simulation was created and coupled to a user-friendly interface, users might be able to obtain and analyze the desired results instead of being constrained by the design space previously determined.

- Even though the authors attempt to describe the simulation methodology and assumptions in the report, it lacks details of the models employed, which makes it hard to determine if refinements need to be made, or even if more appropriate models/methods should be used. It is understandable that, due to the proprietary data, it is not possible to present everything. However, without any of this information, the RSM results are more difficult to interpret.

Specific suggestions regarding models that need more detailed coverage are given below:

Engines and Engine Models (Sections 4.1 and 6.3)
It is not clear whether the engine maps in the simulation tool were generated based on simulations or existing experimental data, somehow fitted and scaled to the various configurations. In general, the explanation on how maps were obtained is vague for such an important component. In one section, the report states that the fueling maps and other engine model parameters used in the study were based on published data. If so, it would be nice to have a list of the published materials that have been used as the resource. In Section 4.2, the report states that the performance of the engines in 2020-25 were developed by taking the current research engines and assuming the performance of the 2020 production engines will match that of the research engine under consideration. Does this assumption take into account the emission standards in 2020, and do the current research engines match those emission standards? What is the systematic methodology that has been adopted to scale the performance and fuel economy of current baseline engines to engine models for 2020-25? Also, the report lacks detail concerning the methodology of extrapolating from available maps to maps reflecting the effects on overall engine performance of the combination of the future technologies considered.

The report lacks detail on the specifics on the different engine design and operating choices. For instance, what was the compression ratio (and limit) that was used? What is the equivalence ratio, or range considered, for the lean burn engine? How much EGR has been used across the speed and load range? What constraints, if any, were applied to the simulations to account for combustions limitations such as knock and flammability limits? The NOx aftertreatment/constraints section could also be expanded.

In cases where engine models have been used to generated maps, how was combustion modeled? For instance, discussion is made as to the heat transfer effect resulting from surface to volume changes connected to downsizing. More detail on the heat transfer assumptions that go into the applied heat transfer factor would be helpful. Was heat transfer modeled based on Woschni's correlation? What about friction scaling with piston speed? This would change with stroke at a constant RPM. Also friction would change with the number of bearings and cylinders.

Turbocharger systems (Section 4.1.3)
There is no discussion of turbocharger efficiencies and their range. Did the simulations assume current boosting technologies? Were maps used for this simulation or some other representation? Was scaling used? What were the allowed boost levels?

Intelligent Cooling Systems (Section 4.3.1)
The report describes intelligent cooling systems, but does not provide any estimates of the anticipated reductions in fuel consumption over the FTP cycle, though related papers have been published in the open literature.

Sizing of various cooling components plays a very crucial role in fuel economy predictions. The report does not provide any detail on how the optimum cooling flow required for a given engine- transmission combination was determined. This would significantly affect the oil, coolant and transmission oil pump RPMs, which would in turn significantly change the accessory loads.

In addition, the report does not have any discussion on how modified cooling components (radiator, condenser, etc.) would be sized for more efficient powertrains. For instance, a more efficient engine that would reject less heat would likely need a smaller radiator and lesser airflow through the radiator; hence, the grill opening could be reduced to cut down on aero drag. A high efficiency transmission will not reject a lot of heat to the transmission oil; thus, a smaller transmission oil cooler could be used.

Warm-up methodology (Section 6.3.1)
This section talks about using engine warm-up profile during the cold start portion to ascertain additional fueling requirements. It talks about a correction factor to account for this additional fuel. How was this factor determined? Has a different correction factor been used for various engines? For instance, for a lean-burn engine that reject less heat, the oil warm-up is slower compared to a baseline engine. Was a new heat rejection map generated to account for start-up enrichment while modeling the warm-up? What is the ambient temperature that has been considered while performing the FTP 75 fuel economy test? Have the viscous effects of engine oil considered in the warm up simulation? How have the friction losses for various valvetrain engine combinations been modeled?

Accessories Models (Section 6.3.2)
Alternator efficiency has been assumed to be constant around 55% for baseline. In the current baseline vehicles the alternator efficiencies do vary with the temperature and load.

Has AC compressor load been considered in any of the simulations? In some of the new cycles being proposed by EPA, it is required that AC remains ON throughout the cycle. Hence, management of the AC load is very critical.

Transmission Models (Section 6.4)
The transmission efficiencies vary by almost 10-15% based on the transmission oil temperature. How have these effects been modeled?

Constraints
There is no discussion in the report that discusses the constraints on the combinations that can be implemented in real life. For example, would a multi-air system that is currently designed for small size engines work for a full size car?

(3) **Results**. Please comment on the validity and applicability of the results to the light-duty vehicle fleet in the 2020-2025 timeframe. Please comment on any apparent unstated or implicit assumptions that may affect the results, and on any related caveats or limitations.

- For the vehicle performance simulation results shown in Table 7.1, were there any significant adjustable parameters used to fit these vehicles?

- Even though it appears that the validation results from the simulation have "acceptably" close agreement with the test data, there are up to 15% off. Even for the small car where all data is available, the error is on the order of 5%. These discrepancies are usually not negligible and should be taken into account when conclusions are drawn from the results, especially if regulation is to be proposed based on these.

- There is also no baseline hybrid configuration and no validation of the hybrid model. Due to the increased complexity of these vehicle systems, it is important to ensure the parameters and assumptions are valid.

- It would be desirable to include a complete test case with the appropriate inputs, analysis and outputs as part of the report. The sample results presented in figures seem to have been included to indicate the RSM and Data Visualization Tool's capabilities, but they do not provide a complete picture from which to draw solid conclusions.

- The plots showing simulation results in blue, red, etc. could be better labeled (i.e. legends could be inserted in the plots) and possibly presented in a relative format indicating percent improvements over the baseline engine rather than absolute numbers. This is more of a personal choice for a more clear representation of the predicted improvement, rather than stating that there is anything wrong with the current representation.

(4) **Completeness.** Please comment on whether the report adequately describes the entire process used in the modeling work from input selection to results.

- Some of the aspects lacking form the report have already been mentioned and discussed in the relevant sections.

- In general, the report provides a fair description of the modeling process. Unfortunately, there are no equations, plots or maps showing any specific modeling item, thus making this part of the report vague.

- It might be possible to shorten the descriptions related to the individual technologies implemented and their improvements and add more details on how they have been modeled. People using this tool will most likely not use the brief descriptions of the various technologies to draw conclusions and make decisions.

- The "Conclusions" section of the report should be renamed "Summary" since it does not present any actual conclusions based on the results, but it does provide a summary of the project.

(5) **Recommendations.** Please comment on the overall adequacy of the report for predicting the effectiveness of these technologies, and on any improvements that might reasonably be adopted by the authors for improvement. Please note that the authors intend the report to be open to the community and transparent in the assumptions made and the methods of simulation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

- Various suggestions have already been included in the relevant sections.

- The authors should expand the modeling sections. In particular, they should cite literature references (where possible) and provide more detail when empirical data, modifiers, or scaling laws are used.

- Flexibility should be added to the models. Some engine technologies, such as variable cam phasing, HCCI and alternative fuels should be considered.

- A self-contained study should be presented as a test case for the results so that specific conclusions can be drawn and the utility of the approach more easily understood.

(6) **Other comments**. Please provide your comments on report topics not otherwise captured by the aforementioned charge questions.

It would be desirable to show the analysis used to convert fuel consumption savings to vehicle greenhouse gas (GHG) emissions equivalent output. Ultimately, what matters is the GHG savings resulting from the combined production and use cycle of alternative fuel options for combustion engines.

Some additional detailed comments on specific sections are given below.

<u>Advanced Valvetrains (Section 4.1.1)</u>
The report states that advanced valvetrain systems improve fuel consumption and GHG emissions mainly by improving engine breathing. Other benefits cited are in supporting engine downsizing and faster aftertreatment warm-up. Beyond improving volumetric efficiency and reducing pumping losses, advanced valvetrains can enable compression ratio variation to increase fuel economy and avoid knock, alter the combustion process by modulating trapped residual, and enable cylinder deactivation to reduce pumping losses. From the report, it is not clear which of the possible benefits of the advanced valvetrain packages have been harnessed in each case. A more systematic analysis of technology package combinations is warranted as several are synergistic but not additive.

<u>Boosting System (4.1.3 and 6.3)</u>
A two-stage system is indeed promising for advanced turbocharging concepts. A distinction should be made between series and sequential configurations. Air flow manipulation can make it a series system (two-stage expansion and compression) or a sequential system (turbos activated at different rpm). Variable geometry or twin-scroll turbines can be good options for the low or high pressure stages, respectively. A two-stage turbocharging system like this would take

advantage of the lean SI exhaust enthalpy, reduce pumping work (or even aid pumping), avoid mechanical work penalties, improve engine transient response, enable high dilution levels (if desired) and probably help keep in-cylinder compression ratio below 12:1, since significant compression would be done before the cylinder. EGR flow could be driven through a low pressure loop (after the turbines) or an intermediate pressure loop (between the turbines). The resulting turbo lag will depend on the details of the configuration and the control logic used. Note that the assumption of a time constant of 1.5 seconds (as stated in the report) to represent the expected delay may not hold true in all cases.

Lean-Stoichiometric Switching (Section 4.2.2)
The mixed-mode operation considered in the report seems to switch between stoichiometric and lean SI direct injection operation. There are several multi-mode combustion efforts under development that encompass several more combustion modes, including HCCI and Spark-assisted compression ignition with amounts of EGR dilution.

P2 Parallel Hybrid (Section 4.3.2)
P2 refers to pre-transmission parallel hybrid, where an electric machine is placed in between the engine and the transmission. While the report does not discuss details, there are two possible configurations: (i) a single clutch, located in between the engine and the electric machine, such as in the Hyundai Sonata, and (ii) two clutches, one in between the engine and the motor, and the other one in between the motor and the transmission, such as in the Infiniti M35 HEV. The P2 system looks promising to achieve good efficiency, but remaining barriers include cost, drive quality, durability and to a lesser extend packaging. Careful consideration of details is needed to properly assess benefits compared to a single mode power split. Early reports have indicated that Nissan got 38% mpg increase out of their P2 and Hyundai got 42%, both with higher horsepower, as well. However, the P2 Touareg doesn't seem to meet EPA 2012 CAFE standards.

Transmission Technologies (Section 4.4)
What about automatic transmissions with automated clutch replacing the torque convertor and lock-up clutch? This is also a possibility.

Efficient Components (Section 4.4.9)
Efficient components should also include gears since rotating gears are also a major source of drag. Designing a better profile for gear teeth can reduce drag losses.

Transmission Models (Section 6.4)
It is claimed that gear selection will be optimized for fuel economy for a given driver input and road load. Can this also be adaptive? Engine performance degrades with age. This strategy could also lead to more gear shifts; the latter would increase hydraulic loads and frictional power losses in the clutch, thus eroding some of the possible fuel economy gains.

Peer review of the report, "Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe"

Report by: Scott McBroom

Date of Report: May 15, 2011

Charge to Peer Reviewers:

As EPA and NHTSA develop programs to reduce greenhouse gas (GHG) emissions and increase fuel economy of light-duty highway vehicles, there is a need to evaluate the effectiveness of technologies necessary to bring about such improvements. Some potential technology paths that manufacturers might pursue to meet future standards may include advanced engines, hybrid electric systems, mass reduction, along with additional road load reductions and accessory improvements.

Ricardo Inc. has developed simulation models including many of these technologies with the inputs, modeling techniques, and results described in the Ricardo Inc. document that you have been provided dated March 10, 2011.

EPA is seeking the reviewers' expert opinion on the inputs, methodologies, and results described in this document and their applicability in the 2020-2025 timeframe. The Ricardo Inc. report is provided for review. We ask that each reviewer comment on all aspects of the Ricardo Inc. report. Findings of this peer review may be used toward validation and improvement of the report and to inform EPA and NHTSA staff on potential use of the report for predicting the effectiveness of these technologies. No independent data analysis will be required for this review.

Reviewers are asked to orient their comments toward the five (5) general areas listed below. Reviewers are expected to identify additional topics or depart from these general areas as necessary to best apply their particular set of expertise toward review of the report.

Comments should be sufficiently clear and detailed to allow readers familiar with the report to thoroughly understand their relevance to the material provided for review. EPA requests that the reviewers not release the peer review materials or their comments until Ricardo Inc. makes its report and supporting documentation public. EPA will notify the reviewers when this occurs.

Below you will find a template for your comments. You are encouraged to use this template to facilitate the compilation of the peer review comments, but do not feel constrained by the format. You are free to revise as needed; this is just a starting point.

If a reviewer has questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If a reviewer has any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

Charge Questions:

(1) **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Examples might include: engine technology selection, battery SOC swing, accessory load assumptions, etc.) Please comment on any caveats or limitations that these inputs and parameters would affect the final results.

(Section 3.2 Ground Rules for Study) The vehicle and technology selection process needs further discussion. My experience in these large simulation studies is that the vast majority of the time needs to be spent on the selection and once selected agreeing upon the model/data.

(Section 4) There was no model data provided. Engine maps, transmission efficiency maps, battery efficiency maps etc need to be in the Appendices. The black box nature of the inputs is disconcerting.

(Section 4.1.1.1 CPS) How were the profiles selected? Was there an optimization process for each engine size of a given engine type?

(Section 4.1.1.2 DVA) Was the actuation power requirement accounted for? What were the timing/lift profiles and what control strategy was used to select the timing/lift profile? Was this an active model or was the timing/lift profile preset and then unchangeable. I would expect that as the engine size changes and the boost changes the timing/lift profile will have to change with it.

(Section 4.1.3 Boosting Systems) What about superchargers? Eaton's AMS supercharger systems offer high efficiency supercharges that are comparable to turbo's and don't have the lag problem.

(Section 4.1.4 Other Engine Technologies) regarding global engine friction reduction, what value(s) was assigned to that? Was it the same across all engines? If so, why?

How was the FEAD electrification energy balance accomplished? Was additional load placed on the alternator?

No mention or consideration of cylinder deactivation technologies. This seems like pretty low hanging fruit, even on downsized boosted engines, especially if you deploy DVA.

(Section 4.2 Engine Configurations) Quantification needed …"The combinations of technologies encompassed in each advanced engine concept provide benefits to the fueling map…."

How were baseline BFSC maps modified? Was it across the board improvement or were improvements only attributed to certain parts of the map?

(6.3 Accessories) I think the assumption that LDT cooling fans will be engine driven is incorrect. The new F150's have electric fans.

Limiting the alternator to 200A is very conservative, particularly if the system voltage stays at 14V.

Is there any accounting for the energy conversion on hybrids from the high voltage bus to the low voltage?

(6.4 Transmission Models) no efficiency maps, no description of the efficiency maps. What was efficiency a function of? Typically it’s gear ratio, torque and speed.

(2) **Simulation methodology.** Please comment on the validity and applicability of the methodologies used in simulating these technologies with respect to the entire vehicle. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations. Does the model handle synergistic affects of applying various technologies together?

(Section 3.4 CSM Approach) Is the CSM approach used in other applications? If so it would be helpful to give citations. If it was developed by Ricardo, that should be stated. The discussion refers to physics based models, but other than that very little about the type of modeling is discussed. I recall on the phone call that lumped parameter models were mentioned. There is no discussion of that.

Some assessment of the model uncertainty would be helpful. This could be a qualitative rating assigned by the advisory committee or a more rigorous method could be used.

More detail on the types of models is required. Do some models use first principals of physics and others lumped parameter?

ANOVA or some other analytical approach to consider technology interactions needs to be deployed.

It says a statistical analysis was used to correlate variations in the input factors to variations in the output factors. This is ambiguous. What analysis method was used? Where is it reported? I didn't see anything in the results about this. It was used to generate the RSM, but what was the measure of fitment? How did the RSM fit compare from vehicle config to vehicle config

(Section 4.1.1 Advanced Valvetrains) There is no explanation of how CPS and DVA systems were modeled. There was only a description of what CPS and DVA is.

(Section 4.2.1 Stoich DI Turbo) Quantify how did the cooled exhaust manifold/lower turbine inlet temp improved the BSFC map. This is a good example of technology interaction…how did the radiator size grow to accommodate the additional heat rejection; how did the frontal area of the vehicle change to accommodate the larger radiator?

(Section 4.2.2 Lean Stoich Switching) This type of tech points to one of the dangers of optimizing configuration/technology/control strategy to the drive cycles; that is that it has the potential to over constrain the design and effect the "real world" performance/fuel economy.

(Section 4.2.4 Atkinson Cycle) How do the 2020-2025 maps differ from the 2010 maps?

(Section 4.2.5 Advanced Diesel) Why were only the benefits of improved pumping losses or friction considered? What improvements were assigned to these benefits? Was it across the board or regional? What about advanced boosting technology for these engines?

Ricardo's expectation for pace and direction: I thought there was an advisory committee making these decisions. I'm surprised that they think boost will be limited to 17-23bar.

(4.4 Transmission Technologies) How were the gear ratios selected? What about shift logic?

(Section 6 Vehicle Models) No discussion of how driveline inertia is handled. This is important in forward-looking models.

There are several types of rolling resistance models, what type was used?

Was coast-down data from the baseline vehicles obtained or where the coefficients of rolling resistance and Cd modified to get the data to match?

(6.3 Engine Models) two methods to develop engine models were discussed. It is not disclosed which approach was used for which engine. I recommend that one approach be developed for all engines or both approaches be applied to each engine to converge to a solution.

Regarding engine downsizing, I'm not sure that the scaling approach applies to boosted engines, especially engine with multiple compressors as well as DVT and CPS technology.

Turbo lag applied as a first order transfer function with a time constant. How was the time constant selected? Was it validated? How was the improvement attributed to turbo compounding modeled?

(6.3.1 Warm-up Methodology) How was the engine warmup modeled? Is it a first order transfer function with a time constant? It said proprietary data was used, but how? Does the method allow for different warmup depending on size and engine technology?

(6.3.2 Accessories) Constant alternator efficiency and load is not a very good assumption. New alternator technologies and higher alternator loads due to electrification and increased electrical demands. Will the future still continue to use 14V or will higher voltages be used?

(6.8 Hybrids) Were separate optimization runs to determine the best control strategy done? How are we assured the best control strategy is implemented?

(7.2 Nominal Runs) Was a separate matrix of simulations run to obtain the nominal sizes for the advanced engine or was it merely a matter of matching the peak torque.

How was a 20% reduction in engine size for the nominal hybrid engine arrived at? Even for the micro-hybrid (engine start/stop)?

"These summary results….used to assess the quality of the simulation…." Where is the data for this assessment published? What were the criteria that said pass or fail?

(3) **Results**. Please comment on the validity and applicability of the results to the light-duty vehicle fleet in the 2020-2025 timeframe. Please comment on any apparent unstated or implicit assumptions that may affect the results, and on any related caveats or limitations.

(Section 4.4.6 Shifting Clutch Technology) "The technology will be best suited to smaller vehicle segments because of reduced drivability expectations" – not in the US market.

(Section 4.4.7 Improved Kinematic Design) Assumes a sweeping improvement without identifying a clear rationale…doesn't appear to describe a scientific or objective approach.

(Section 4.4.11 Lubrication) Assumes a sweeping improvement without identifying a clear rationale…doesn't appear to describe a scientific or objective approach.

(Section 4.5.1 Intelligent Cooling System) The system as described seems more appropriate for regulated emissions reduction opportunity rather than fuel economy or GHG. I think these systems enable engine control strategies that aren't part of this study that would have a greater impact on fuel economy than warming up the engine faster.

(5.2 Vehicle Configuration and technology combinations) Also there is no scientific or objective reason given for the DoE ranges. It appears that I can make any vehicle 60% less mass, 70% less rolling resistance etc.…This will skew the results towards that end of the DoE, when they may not be practically achievable.

(6.1 Baseline Conventional Vehicle Model) Results were compared to the EPA Vehicle Certification Database. These results often include correction factors and allowances that aren't documented on the sticker. Recommend that actual testing be run to perform the benchmark.

(6.3.1 Engine Warmup Methodology) Were there hot and cold engine maps? No mention.

(6.4 Transmission Models) Fig 6.1 appears to be a comparison of desired cvt ratio vs desired 6spd gear ratio. Should be stated as such. The shift logic controller should take into account the time to shift and whether or not the desired shift is achievable.

What are the shift optimizer inputs? What are it's basic decision criteria?

There is no discussion of engine downspeeding.

There is no discussion of gear ratio selection.

(6.5 torque Converter models) The lockup strategy seems very conservative. Large gains are achievable with more sophisticated control and are in use today.

What was the basis for the minimum rpm's for lockup sited? Should be based on lugging the engine. The controller should recognize when it needs to unlock the TC based on the engines ability to keep up.

(6.6 Final Drive Model) Only discussed the baseline, what improvements for 2020 and what final drive selection criteria for the future vehicles was used?

(6.7 Driver Model) How was the soak modeled? Were there hot engine maps and cold engine maps?

(7.1 Baseline Conventional Vehicle Models)
Better definition of what "acceptably close" means. This doesn't meet the criteria for objectivity. Something like, "the advisory committee determined that the baseline models had to predict within x% to be usable for this study."

On the performance runs, a few tenths of a second represent measurable difference in engine torque for example.

(8.1 Evaluation of Design Space) Why was Latin hypercube sampling methodology picked over other sampling methods? While it's attributes are mentioned, what other methods were considered?

(8.2 RSM) A description of how the neural network is deployed is needed, only the why it was used is discussed in this section. What were the best fit criteria? What types of equations did the neural net have to play with? Where are the fit's published? How was it determined that the "one fit per transmission" was the best way to go?

(9.1 Basic Results) Why 10Hz sampling rate? By what criteria was a run considered good vs bad?

(9.3 Exploration of the Design Space) If boundaries of acceptable performance were applied, a considerable number of simulation runs could be eliminated.

(4) **Completeness.** Please comment on whether the report adequately describes the entire process used in the modeling work from input selection to results.

(Section 2 Objectives) A discussion of appropriate/anticipated use of the results is required.

(Section 3.3 Ground Rules) How did the group arrive at the seven vehicles? While it show comprehensiveness, it's possible to see that there could be some overlap. If one looks at the engine and transmissions packages available in these vehicles already you can see the overlap. Reducing the number of vehicles might save on the number of runs you'll need to make.

(Section 3.3 Technology Selection Process) Who is on the Advisory Committee? Is it independent? How did the program team come up with the comprehensive list of potential technologies? (From the phone call it sounded like it was based on what models Ricardo had in their library. This is concerning.)

It said there was a comprehensive list of technologies that the group started with, that list should be shown and a comment on why it wasn't included.

Why wasn't HCCI technology considered? From the publications this seems to be a candidate for production in the next 10 yrs.

(Section 4. Technology Review and Selection) Regarding qualitative evaluation of technology "Potential of the technology to improve GHG emissions on a tank to wheels basis", since this was a qualitative assessment I think it would be better to include well to wheels.

Regarding "Current (2010) maturity of the technology", how was maturity ranked?

Citations required for statement " SI engine efficiency to approach CI efficiency in the time frame considered" This represents relatively large gains in SI technology compared to CI, however EU and Japanese engine companies are making big improvements on CI as well.

(Sections 4.1 and 4.2) There's no descriptions of the models. There are only descriptions of the technologies and their perceived benefits. The reader has to assume that the same modeling approach was used to model each technology, but I know from personal experience this is very difficult and most likely not the case.

(Section 4.1.2 DI Fuel Systems) No discussion of DI control strategy. How was it selected? Was there a separate optimization of DI control or was it one size fits all?

(Section 4.1.3 Boosting Systems) It says that other boosting systems were included in the study, but only turbocharging is discussed.

(Section 4.3 Hybrids) Don't see any data on the battery technology, battery management, SOC control strategies. No discussion of regen braking strategies.

(Section 4.3.1 Micro Hybrids) It is implied that electrified accessories aren't used in this configuration. I don't see that as the case.

(Section 4.3.2 P2 Hybrid) No discussion of why DCT was only transmission used for P2 hybrids instead of CVT and AMT.

(4.4 Transmission Technologies) What types of CVT's were in the original mix? Toroidals, push-belts, Miller?

No transmission data was shown. No mass, no inertia to efficiency maps, no gear ratios.

(4.4.1 Automatic Transmission) No logical explanation for the 20-33% improvement…how was this number arrived at?

(4.4.3 Wet clutch) It said these were expected to be heavier, cost more and be less efficient than DCT's so why where they included?

(4.4.10 Super Finishing) How much improvement is attributed to super finishing?

(4.5 Vehicle Technologies) No values for mass, rolling resistance or drag given. No discussion of the improvement possibilities. This would be a good place to use historical trends for vehicle mass reduction, aero improvements and parasitic loss improvement.

(5.2 Vehicle Configuration and technology combinations) While the tables show the vehicle configurations, more discussion regarding the selection criteria for each vehicle is warranted. In some cases this discussion was attempted in the technology sections, but I don't think it should go there.

(Section 6 Vehicle Models) No discussion of how driveline inertia is handled. This is important in forward-looking models.

There are several types of rolling resistance models, what type was used?

(6.8 Hybrid Models) Too much data is missing. What were the pack voltages? What were the battery technologies? Was there only one or more? Other than improved resistance, what other future improvements were included, like improved power density, improved usable SOC range? What was the control strategy for each type?

Load leveling the engine by charging the batteries has been shown to not be a very good idea because the round trip efficiency hit is a killer. Should only be used when SOC falls below a certain level.

We're left to assume that SOC leveling is accomplished, but there is no description of how? Was an EPA/SAE method used.

When it comes to GHG reductions why weren't plug-in hybrids considered?

(5) **Recommendations.** Please comment on the overall adequacy of the report for predicting the effectiveness of these technologies, and on any improvements that might reasonably be adopted by the authors for improvement. Please note that the authors intend the report to be open to the community and transparent in the assumptions made and the methods of simulation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

1) Instead of using proprietary Ricardo data/models/control algorithms citable data should be used.
2) Without stating how this model is going to be used in the regulatory decision making process, it is very difficult to assess its appropriateness.
3) Considerably more time in this effort is required up front in the report, to discuss the process of building consensus on data and models. Because this is not really discussed, it gives the impression that not much was done.
4) Guidelines for appropriate use should be given.
5) An uncertainty rating for each model/data set should be published to highlight the relative differences in the assumptions/extrapolation of future technologies.
6) Should use coast down data for baseline vehicles to model parasitic losses.
7) In terms of acceptable use: rather that trying to use the model to assess the boundaries of the envelope (or which technology is better), the tool could be used to find the areas of maximum overlap. In other words, knowing that the same performance and fuel economy is achievable using different technologies lends more confidence that the result is achievable. Theoretically this number could be a calculated value generated from the RSM's.
8) Recommend allowing "real world" drive cycles to assess the robustness of the results. Could be a user generated result from a composite of the data sets already generated.
9) Should define the process for data selection….eventually you'll be asked by a manufacturer, 'how do we get 'x' technology included for consideration in the study.
10) Where lumped improvements are made, I recommend using historical results to publish technology improvement curves. For example, the parasitic losses (Cd, Crr) should be quantifiable. Vehicle mass reductions as well.

(6) **Other comments**. Please provide your comments on report topics not otherwise captured by the aforementioned charge questions.

Scott McBroom

Having conducted a similar effort for USCAR on the PNGV program, I understand that considerable effort is required to develop such a model. I don't want to diminish all the hard work that was done, by only offering criticism in the above sections. It appears that the intent of the approach to this activity is in the right place, just better documentation is needed and appropriate use guidelines.

PEER REVIEW:

Computer Simulation of Light-Duty Vehicle Technology for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe

Review Conducted for:

U.S. EPA

Review Conducted By:

Shawn Midlam-Mohler

Review Period:

4/28/2011 – 5/16/2011

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Executive Summary

For the purpose of describing the modeling approach used in the forecasting of the performance of future technologies, the report reviewed is inadequate. In virtually every area, the report lacks sufficient information to answer the charge questions provided for the reviewer. It is entirely possible that the approach used is satisfactory for the intended purpose. However, given the information provided for the review, it is not possible for this reviewer to make any statement regarding the suitability of this approach. Some brief comments on each of the five charge questions are provided below:

Inputs and Parameters – From a high level, it is clear what the inputs to the design space tool are, which are listed in tables 8.1 and 8.2. At the next level down (i.e. the vehicle and subsystem models) there is no comprehensive handling of inputs in parameters in the report. Some models are partially fleshed out in this area but most are lacking. By way of example, the engine models are described as maps which are "defined by their torque curve, fueling map, and other input parameters" where "other input parameters" are never defined.

Simulation Methodology – The vehicle model is reported as "a complete, physics-based vehicle and powertrain system model" - which it is not. The modeling approach used relies heavily on maps and empirically determined data which is decidedly not physics-based. This nomenclature issue aside, the model is not described in sufficient detail in the report to make an assessment in this area. An excellent example of this is the electric traction drives and HEV energy storage system for which the report mentions no details, even qualitative ones, on the structure of the models.

Results - The third charge questions deals with the validity and the applicability of the resulting prediction. The difficulty in this task is that it is an extrapolation from present technology that uses an extrapolation method (*i.e.* the model) and a set of inputs to the model (*i.e.* future powertrain data.) Since it is not possible to validate the results against vehicles and technology that do not exist, one can only ensure that the model and the model inputs are appropriate for the task. Because of the lack of transparency in the model and inputs it is difficult to make any claims regarding the results. In trying to validate results, one example is cited in the body of the report that shows the baseline engine getting superior HWFET and US06 fuel economy than all of the other non-HEV powertrains with other factors being the same – this leaves some skepticism regarding the results.

Completeness – Based on the above, it is clear that this reviewer feels the report is inadequate at describing the entire process of modeling work from input selection to results. There was not a single subsystem that was documented at the level desired. It is understood that, in some cases, there are things of a proprietary nature that must be concealed. As a trivial example, the frontal area of the vehicle classes does not seem to be anywhere in the report or data analysis tool. This is one parameter amongst hundreds excluding the real details of the models (*i.e.* equations or block diagrams), methods used to generate engine maps, details on control laws, *etc.* On the topic of proprietary data, there are many ways of obscuring data sufficiently that can demonstrate a key point (i.e. simulation accuracy) without compromising confidentiality of data – this should not be a major barrier to providing some insight into the inner working of the simulator.

Recommendations – Given the low level of detail given in the report, it does seem that the strategy used is consistent with the goal of the work and what others in the field are doing. That being said, the report is inadequate in nearly every respect at documenting model inputs, model parameters, modeling methodology, and the sources and techniques used to develop the technology performance data. Given the need for transparency in this effort, this reviewer feels that the detail in the report is wholly inadequate to document the process used. *The organization responsible for the modeling has expertise in this area it is certainly possible that the methodology is sound, however, given just the information in the report there is simply no way for an external reviewer to make this conclusion.*

Because of the lack of hard information to answer the charge questions, this peer review evolved mainly into a suggested list of details that should be brought forward in order to allow the charge questions to be answered properly. With this information, it is hoped that a person with expertise in the appropriate areas will be able comment on the work more fully.

Simulation Methodology

The simulation methodology is generally not described in the report in sufficient detail to assess the validity and accuracy of the approach. The models and approach are described qualitatively; however, this is insufficient to truly evaluate the ability of the modeling approach to perform the desired function. The following subsections address specific issues with the models, inputs, and parameters and suggest possible corrective actions to address these issues.

Vehicle Model

The vehicle model is described as "a complete, physics-based vehicle and powertrain system model" developed in the MSC.Easy5™ simulation environment. This description is not particularly helpful in defining the type of model as portions of the model are clearly not physics based, such as the various empirical maps used or sub-models like the warm-up model which is by necessity an empirical model due to the complexity of the warm-up process compared to the expected level of fidelity of the model. It is assumed that a standard longitudinal model accounts for rolling losses, aero losses, and grade is used to model the forces acting on the vehicle. Input parameters for the vehicle model are not described. The baseline vehicle platforms are listed, however, the relevant loss coefficients are not provided (rolling resistance, drag coefficient, inertia.)

Suggested Corrective Action:

1. List the dynamic equation describing the longitudinal motion of the vehicle
2. List all parameters used for each vehicle class for simulation

Engine Models

The engine model is the most important element in successfully modeling the capability of future vehicles, since it is the responsible for the largest loss of energy. It is also one of the most difficult aspect to predict since it involves many complicated processes (*i.e.* combustion, compressible flow) which must be considered in parallel with emissions compliance (*i.e.* in-cylinder formation, catalytic reduction.) Because of this, this sub-model must be viewed with extreme scrutiny in order to ensure quality outputs from the model.

The engine models are "defined by their torque curve, fueling map, and other input parameters." This implies that the maps are static representations of fuel consumption versus torque, engine speed, and other unknown input parameters. Generally speaking, representing engine performance in this fashion is consistent with typical practice for this class of modeling.

This comment deals only with the representation of the engine performance in simulation, the generation of the data contained within the map is much more challenging.

The report outlines two methods were used to produce engine models. The first method was used for boosted engines and relied upon published data on advanced concept engines which would represent production engines in the 2020-2025 timeframe. The second method was used with Atkinson and diesel engines and somehow extrapolated from current production engines to the 2020-2025 time frame. The description of both of these methods in the report is unsatisfactory. It also fails to address how the various technologies are used to build up to a single engine map for a specific powertrain. Validation, to the extent possible with future technologies, is also lacking in this area.

This reviewer took some time to look at the data via the tool provided. One table is shown in Figure 1 which shows some unexpected results. The results are for a small car with the dry clutch transmission and it shows the baseline engine having superior fuel economy over all other non-hybrid powertrain options. This is unexpected behavior and, since there is minimal transparency in the model, it cannot be investigated any further.

Engines	FTP	HWFET	US06
Baseline	42.1	62.5	37.0
Stoich_DI_Turbo	46.3	55.3	33.7
Lean_DI_Turbo	48.3	56.4	33.9
EGR_DI_Turbo	48.2	57.6	35.2
Atkinson_CPS	44.5	59.0	35.4
Atkinson_DVA	45.5	57.1	34.5

Figure 1: Simulation Results Different Engines for Small Car with 8Dry_DCT and all other Parameters Constant

<u>Suggested Corrective Action:</u>

1. Provide fuel and efficiency map data for all engines used in simulation
2. Describe what the “other inputs” are to the engine maps
3. Provide specific references of which published data was used to predict performance of the future engines. Some references are given, however, it is not clear how exactly these references are used.
4. Wherever possible, provide validation against data on similar technologies
5. Describe in detail the approach used to “stack up” technologies for a given powertrain recipe

Aftertreatment/Emissions Solutions

Based on the report, it seems that emissions solutions are assumed to be available for all powertrain technology packages selected. The report discusses this in some qualitative detail in section 4.2.2 with respect to lean-stoichiometric switching. This discussion is somewhat incomplete, in that the way it is written it assumes operating at stoichiometry lowers exhaust gas temperature. In reality, switching from lean to stoichiometric operation at constant load results in higher exhaust gas temperatures. Despite this factual inconsistency, it is indeed generally better to operate a temperature sensitive catalyst hot and stoichiometric or rich rather than hot and lean – so the concept of lean-stoich switching is valid even if the explanation provided is not. Even without this factual inconsistency, some additional discussion of aftertreatment systems would be of benefit given that lean-burn gasoline engines are at present a well-known technology for many years that is still problematic with respect to emissions control. A separate issue is the topic of fuel enrichment for exhaust temperature management which will have an important impact on emissions and, if emissions are excessive, reduce the peak torque available from an engine.

Suggested Corrective Action:

1. Provide better evidence that powertrain packages have credible paths to meet emissions standards
2. Provide evidence that fuel enrichment strategies are consistent with emissions regulations

Advanced Valvetrains

Two types of advanced valvetrains were included in the study, cam-profile switching and digital valve actuation. Both of these technologies are aimed at reducing pumping losses at part-load. The impact of these technologies is difficult to predict using simplified modeling techniques and typically require consideration of compressible flow and a 1-D analysis at a minimum. Even with an appropriate fidelity model, these systems require significant amounts of optimization in order to determine the best possible performance across the torque-speed plane of the engine. It is unclear how these systems were used to generate accurate engine maps given the level of detail provided in the report.

Suggested Corrective Action:

1. Describe how variable valve timing technologies were applied to the base engine maps
2. Describe the process of determining the extent of the efficiency improvement
3. Describe how optimal valve timing was determined across the variety of engines simulated

Direct Injection Fuel Systems

Because of the availability of research and production data in this area, it is expected that performance from this technology was used to predict performance rather than any type of modeling approach. That being said, the report does not describe where or how this data might have been used to develop the fuel consumption map of the engines simulated nor what data sources were used.

Suggested Corrective Action:

1. Cite sources of data used to predict DI performance
2. Describe how this data was used to develop the future engine performance maps
3. Provide validation of modeling techniques used

Boosting Systems

Boosting was applied to many of the different powertrain packages simulated. Beyond stating what maximum BMEP that was achievable, very little is mentioned in how the efficiency of the boosted engines were determined. Among other factors, boosting often creates a need for spark retard which costs efficiency if compression ratio is fixed. These complex issues are tied to combustion which is inherently difficulty to model. This aspect of the engine model is not well documented in the report.

Suggested Corrective Action:

1. Describe the process of arriving at the boosted engine maps
2. Describe how factors like knock are addressed in the creation of these maps

Engine Downsizing

Engine scaling is used extensively in the report. Basic scaling based on brake mean effective pressure is common in modeling at this level of fidelity, thus, this does not need any special description. However, the report mentions some means of modeling the increased relative heat loss with small displacement engines which is not a standard technique. The model or process used to account for this effect should be explicitly described given that engine size is one of the key parameters in the design space.

Suggested Corrective Action:

1. Properly document the process of scaling engines
2. Validate the process used to scale engines

Warm-Up Methodology

The report describes a 20% factor applied to bag 1 of the FTP-75 for baseline vehicles and a 10% factor applied to the advanced vehicles. The motivation for these factors is described qualitatively and is valid, as many organizations are currently investigating strategies to selectively heat powertrain components to combat friction effects. However, the values for these factors that were selected are not backed up with any data or citation. It is suspicious that the two values cited are such round numbers - the data from which these numbers are derived should be cited. Because of the complexity of this phenomenon, some type of empirical model is justified. The model described in the report is not sufficiently validated to judge its suitability.

Suggested Corrective Action:

1. Cite sources of data for 10% and 20% factors applied to the cold bag fuel economy data
2. Cite and/or validate the modeling approach used

Accessory Models

The accessory model is divided into electrical and mechanical loads. The electrical sub-model assumes alternator efficiency's of 55% and 70% for the baseline and advanced vehicles respectively. Given the required simplicity of the model, a simple model like this is likely acceptable, however, there is no source described for the alternator efficiencies. The base electrical load of the vehicle is mentioned briefly, however, no numerical values are given for each vehicle class or any type of model described.

The electrical system also includes an advanced alternator control which allows for increased alternator usage during decelerations for kinetic energy recovery. The control description given is valid but simplistic, but seems to fit the expected level of accuracy required for the purpose. There is an issue regarding with the approach for modeling the battery during this process. When charging the battery at the stated level of 200 amps, the charging efficiency of the battery will be relatively poor. During removal of the energy later, there will once again be an efficiency penalty. There is no description of a low-voltage battery model in the report nor any explicit reference to such charge/discharge efficiencies. Additionally, an arbitrary limit of a 200 amp alternator is defined for all vehicle classes – it is unlikely that a future small car and a future light heavy duty truck will have an alternator with the same rating.

On the mechanical side, it is assumed that "required accessories" (*e.g.* engine water pump, engine oil pump) are included in the engine maps. The mechanical loading of a mechanical fan is mentioned but no description of the model which, at a minimum, should be adjusted based on engine speed and engine power.

Suggested Corrective Action:

1. Cite and/or validate the alternator efficiency values of 55% and 70%
2. Account for charge/discharge losses in the advanced alternator control and/or describe the 12V battery model used for the simulation
3. Describe, cite, and validate the accessory fan model used in the simulation
4. Justify the use of a 200 Amp advanced alternator across all of the vehicle platforms.

Engine Technology "Stack-Up"

There are a host of different technologies superimposed to create the future powertrain technologies. There is not a clear process described on how this technology "stack-up" is achieved. For instance, an advanced engine technology may allow for greatly improved BMEP. Greatly improved BMEP often comes at the expense of knock limits which are difficult to model even with sophisticated modeling techniques. In this simulation, many layers of powertrain technology are being compounded upon each other which will not simply sum up to the best benefits of all of the technologies – there are simply too many interactions. At the level of modeling described, which are maps which are altered in various unspecified ways; it is not clear how the technology stack-up is captured.

Suggested Corrective Action:

1. Describe in greater detail the approach used to model technology stack-up on the advanced vehicles
2. Provide some form of validation that this approach is justified

Baseline Hybrid Models

The following subsections deal with issues related to the hybrid component models.

Hybrid Control Strategy

Hybrid vehicles are particularly challenging to model because of the extra components which allow multiple torque sources, and thus, require some form of torque management strategy (*i.e.* a supervisory control.) The report briefly describes a proprietary supervisory control strategy that is used to optimize the control strategy for the FTP, HWFET, and US06 drive cycle. The strategy claims to provide the "lowest possible fuel consumption" which seems to be somewhat of an exaggeration – this implies optimality which is quite a burden to achieve and verify for such a complicated problem. The strategy also is reported to be "SOC neutral over a drive cycle" which is also difficult to achieve in practice in a forward looking model. Once can get SOC with a certain window, however, short of knowing the future or simply not using the battery - it is impossible to develop a totally SOC neutral control strategy.

Another factor that must be considered is that a hybrid strategy that achieves maximum fuel efficiency on FTP, HWFET, and US06 does not consider many other relevant factors. Performance metrics like 0-60 time and drivability metrics often suffer in practice. In today's hybrids, the number of stop-start events is sometimes limited from the optimum number for efficiency because of the emissions concerns. Because of these factors and others, a strategy achieving optimal efficiency may be higher than what can be achieved in practice.

Without even basic details on the hybrid control strategy, it is simply not possible to evaluate this aspect of the work. Because of the batch simulations with varying component sizes and characteristics, this problem is not trivial. Supervisory control strategies used in practice and in the literature require intimate knowledge of the efficiency characteristics and performance characteristics of all of the components (engine, electric motors/inverters, hydraulic braking system, and energy storage system) to develop control algorithms. This concern is amplified by the lack of validation of the hybrid vehicle model against a known production vehicle. It is unclear how a "one-size fits all" control strategy can be truly be perform near optimal over such widely varying vehicle platforms.

A last comment is that there is no validation of the HEV model against current production vehicles. At a minimum, the Toyota Prius has been dissected sufficiently in the public domain to conduct a validation of this class of hybrid electric vehicle.

Suggested Corrective Action:

1. Better describe the hybrid control strategy and validate against a current production baseline vehicle
2. Validate that the HEV control algorithm performs equally well on all vehicle classes
3. Validate that other vehicle performance metrics, like emissions and acceleration, are not adversely impacted by an algorithm that focuses solely on fuel economy. The emission side of things will challenge to validate with this level of model, however, some kind of assurance should be made to these factors which are currently not addressed at all.

Electric Traction Components

The model of electric traction components is not discussed in any detail, as the only mention in the report is that current technology systems were altered by "decreasing losses in the electric machine and power electronics." Given the importance of the electric motor and inverter system in hybrids this is not acceptable.

Suggested Corrective Action:

1. Describe the method used to model electric traction components
2. Provide validation/basis for the process used to generate future technology versions of these components
3. Describe the technique used to scale these components

HEV Battery Model

Battery models for HEVs are necessary to adequately model the performance of an HEV. The report provides no substantive description of the battery pack model, other than that the model was developed by "lowering internal resistance in the battery pack to represent 2010 chemistries under development." Battery pack size is also not a currently a factor in the model – this has a impact of charge and discharge efficiency of the battery pack.

Suggested Corrective Action:

1. Describe the method used to model the HEV battery

2. Provide validation/basis for the process used to generate future technology versions of the battery
3. Describe the technique used to scale the HEV battery

Transmissions

This peer reviewer is not as well-practiced in transmissions as in other areas in this review. Because of this, a more limited review was conducted of this aspect of the report. As with the other areas of the report, the general concern in this area is the inadequacy of documentation of the modeling approach and validation. Generically, the same issues noted above are applicable here:

1. Cite data sources used in modeling
2. Validate models wherever possible
3. Fully describe transmission models/maps and processes used to generate them
4. Fully describe clutch/torque converter models/maps and processes used to generate them
5. Fully describe the process used to generate shift maps and the operation of the shift controller
6. Fully describe the lockup controller (*i.e.* how soon can it enter lockup after shifting?)
7. Fully describe the process for modeling torque holes during shifting
8. Fully describe the model used for the final drive (*i.e.* inputs/structure/outputs)

Data Analysis Tool

The vehicle simulator is used to generate several thousand simulations using a DOE technique. This data is then fit with a neural-network-based response surface model in which the "goal was to achieve low residuals while not over-fitting the data." This response surface model then becomes the method from which vehicle design performance is estimated in the data analysis tool. In this case, the response surface model is nothing more than a multi-dimensional black-box curve fit. There was no error analysis given in the report regarding this crucial step. By way of example, the vehicle simulator could provide near perfect predictions of future vehicle performance; however, a bad response surface fit could corrupt all of the results.

Suggested Corrective Action:

1. Provide error metrics for the neural network RSMs (*i.e.* R^2, min absolute error, max absolute error, error histograms, error standard deviation, *etc*.) before combining the fit and validation data sets
2. Provide the error metrics described above for the RSMs after combining the fit and validation data sets
3. Provide validation that the data analysis tool correctly uses the RSM to predict results very close to the source data (*i.e.* demonstrate the GUI software behaves as expected)

Conclusions

As outlined in the executive summary, it was not possible to answer the charge questions provided for this peer review due to lack of completeness in the report. Thus, this report was aimed at providing feedback on what information would be helpful to allow a reviewer to truly evaluate the spirit of the charge questions. With the above in mind, the following conclusions are made.

The modeling approach describe in the report *could* be appropriate for the simulation task required and is generally consistent with approaches used by other groups in this field. The conclusions from the report *could* very well be sound; however, there is insufficient information and validation provided in the report to determine if this is the case. The technique used to analyze the mass simulation runs *could* also be sound, although the accuracy of the response surface model is not cited in the report.

These issues are summarized in the following key areas:

1. The process of arriving at the performance of the future technologies is not well described
2. The majority of models are only described qualitatively making it hard or impossible to judge the soundness of the model
3. Some of the qualitative descriptions of the models indicate that models do not consider some important factors
4. Because of the qualitative nature of the model descriptions, there is a major lack of transparency in the inputs and parameters in the models

5. Where precise value(s) are given for parameters in the model, the report generally does not cite the source of the value(s) or provide validation of the particular value
6. Validation of the model and sub-models is not satisfactory (It is acknowledged that many of these technologies do not exist, but the parameters and structure of the model have to be based on something.)

Review of the report

COMPUTER SIMULATION OF LIGHT-DUTY VEHICLE TECHNOLOGIES FOR GREENHOUSE GAS EMISSION REDUCTION IN THE 2020-2025 TIMEFRAME

17 May 2011

Prepared for

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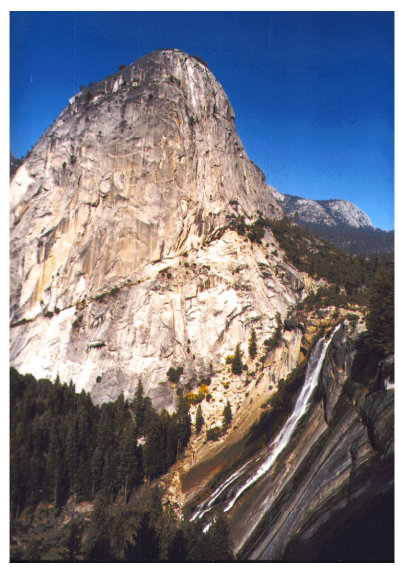

OVERVIEW

This is a review of the report, *Computer simulation of light-duty vehicle technologies for greenhouse gas emission reduction in the 2020-2025 timeframe,* 6 April 2011, prepared by Ricardo, Inc. Additionally the "Complex System Tool," which uses the results of about 500,000 computer simulations to generate fuel economy and CO_2 emissions for combinations of vehicle architectures, engines, and transmissions was examined. Up to 11 parameters may be varied within constrained limits to explore the sensitivity of fuel economy and CO_2 emissions. Jeff Cherry of USEPA/OTAQ assisted in the installation and running of the tool. Examination of the tool provided additional perspective on how the computational results are to be used and the nature of some of the hidden assumptions. This review does not include the Complex System Tool, except as it may reveal the nature of the computer simulation.

Computer simulation of light-duty vehicle technologies for greenhouse gas emission reduction in the 2020-2025 timeframe describes engine and vehicle technologies that are or could be available to improve light-duty vehicle efficiency and thereby reduce carbon dioxide emissions. It does not treat other greenhouse gas emissions or alternative fuels. The Federal Test Procedure (FTP) framework for vehicle certification constrains the analysis, thereby excluding technologies related to vehicle downsizing, reduced performance, and "real world" operation such as driver behavior compensation, air conditioning and heating load management, and loads as affected by speed, acceleration, turning, hills, and wind, all of which are outside of the certification tests.

The work includes the integration of selected technologies through a "data visualization tool" (The Complex System Tool) for assessment of user-elected technologies. The technologies include both drive-train technologies and technologies to reduce vehicle load, such as drag reduction, rolling resistance reduction, light weighting, and improved accessories efficiency (but limited to intelligent cooling systems and electric power steering). Seven light-duty vehicle types represent the 2010 baseline and future 2020-2025 fleets. Battery electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs), and fuel-cell electric vehicles (FCEVs) are not included.

The report describes, qualitatively, the technologies considered in a clear, logical fashion. Because of its proprietary nature, quantitative performance data, such as engine maps, are missing from the report and not accessible for this review.

REVIEW

This review follows the structure of the 'charge questions".

(1) ***Inputs and Parameters.*** *Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Examples might include: engine technology selection, battery SOC swing, accessory load assumptions, etc.) Please comment on any caveats or limitations that these inputs and parameters would affect the final results.*

The vehicle classes and baseline exemplars are reasonably chosen, within the constraint that vehicle size, footprint, and interior volume for each class be locked to the 2010 base year. It is likely that new vehicle classes will emerge by 2025 and/or that these "locking" restraints will be relaxed.

The design of experiment (DoE) ranges, Tables 5.4, 5.5, 8.1, and 8.2, are reasonable and do not exclude likely sizings. The assumed alternator baseline and advanced alternator efficiencies are reasonable. The assumed reduction in automatic transmission losses is reasonable, but not aggressive for 15 development years from the baseline year. Similarly the state-of-charge swing for hybrid modeling of 30-70% is reasonable, but does not reflect improved battery technology for the 2020-25 period, which should allow a greater swing for reduced battery size, weight, and cost.

(2) ***Simulation methodology.*** *Please comment on the validity and applicability of the methodologies used in simulating these technologies with respect to the entire vehicle. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations. Does the model handle synergistic affects of applying various technologies together?*

Ricardo simulated dynamic vehicle physical behavior using MSC Easy5™ software with 10 Hz time resolution. This software and the time resolution are appropriate for the computations to show the effect of component interactions on vehicle performance. 10 Hz time resolution is sufficient to capture both driver behavior and vehicle response. Should the application of information technology, as is being implemented, as a means of vehicle control for reducing fuel consumption become a future strategy, the model should be able to provide a suitable simulation.

Drivetrain synergistic effects seem to be predicted reasonably. This was demonstrated by calculation of fuel economy of the baseline vehicles and comparison with EPA certification test data. The model does not seem to have the capability to capture vehicle weight-drivetrain synergistic effects. Vehicle weight reductions associated with drivetrain efficiency improvements are input rather than modeled internally. This is an important deficiency. Similarly, from the Complex System Tool, weight reductions do not seem to result in reduction in engine displacement.

(3) ***Results****. Please comment on the validity and applicability of the results to the light-duty vehicle fleet in the 2020-2025 timeframe. Please comment on any apparent unstated or implicit assumptions that may affect the results, and on any related caveats or limitations.*

Performance calculations tied to the FTP, HWFET, and US06 test cycles do not adequately capture vehicle behavior under real-world operation. Therefore, technologies that address improving fuel economy under real-world operation are either excluded or their contribution not included. The application of a 20% reduction in fuel economy to the FTP75 bag 1 portion of the drive cycle for 2010 baseline vehicles and 10% for 2020-2025 is crude, arbitrary, and treats only one of many problems with the driving simulation in the test cycles. Test cycle difficulties carry over into the simulation of hybrid control strategies.

It is conceivable that BEVs and PHEVs (and less likely FCEVS) will be a significant part of the 2020-2025 vehicle fleet. That they are excluded from the model is a deficiency.

(4) ***Completeness.*** *Please comment on whether the report adequately describes the entire process used in the modeling work from input selection to results.*

The selection of drivetrain technologies (other than the electric storage technologies) is comprehensive. The qualitative description of the drivetrain technologies is complete and clear, but quantitative performance data are missing. Transparency in the actual performance data is entirely lacking. This includes engine performance maps, shift strategies, battery management in hybrids, and more. That much of that data is proprietary to the companies that generated it and/or to Ricardo is a problem for what is proposed as a regulatory tool.

The assumptions are difficult to extract from the text.

(5) ***Recommendations.*** *Please comment on the overall adequacy of the report for predicting the effectiveness of these technologies, and on any improvements that might reasonably be adopted by the authors for improvement. Please note that the authors intend the report to be open to the community and transparent in the assumptions made and the methods of simulation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.*

The failure to model the drivetrain-weight interactions is a major shortcoming. Appendix 2 should clearly state that vehicle weights are held constant (assuming that I am correct in that assumption).

There should be a table describing the baseline vehicles.

Summarizing assumptions in tabular form would be a great assistance to the reader.

The design space should be expanded to include performance parameters, such as power/weight or 0-60 times.

(6) ***Other comments***. *Please provide your comments on report topics not otherwise captured by the aforementioned charge questions.*

The conclusions, Section 11, are a reasonable summary of the work conducted.

Including the membership of the advisory committee would be appropriate.

Peer review of the report, "Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe"

Report by: Wallace R. Wade

Date of Report: May 15, 2011

Charge to Peer Reviewers:

As EPA and NHTSA develop programs to reduce greenhouse gas (GHG) emissions and increase fuel economy of light-duty highway vehicles, there is a need to evaluate the effectiveness of technologies necessary to bring about such improvements. Some potential technology paths that manufacturers might pursue to meet future standards may include advanced engines, hybrid electric systems, mass reduction, along with additional road load reductions and accessory improvements.

Ricardo Inc. has developed simulation models including many of these technologies with the inputs, modeling techniques, and results described in the Ricardo Inc. document that you have been provided dated March 10, 2011 (version received was dated April 6, 2011).

EPA is seeking the reviewers' expert opinion on the inputs, methodologies, and results described in this document and their applicability in the 2020-2025 timeframe. The Ricardo Inc. report is provided for review. We ask that each reviewer comment on all aspects of the Ricardo Inc. report. Findings of this peer review may be used toward validation and improvement of the report and to inform EPA and NHTSA staff on potential use of the report for predicting the effectiveness of these technologies. No independent data analysis will be required for this review.

Reviewers are asked to orient their comments toward the five (5) general areas listed below. Reviewers are expected to identify additional topics or depart from these general areas as necessary to best apply their particular set of expertise toward review of the report.

Comments should be sufficiently clear and detailed to allow readers familiar with the report to thoroughly understand their relevance to the material provided for review. EPA requests that the reviewers not release the peer review materials or their comments until Ricardo Inc. makes its report and supporting documentation public. EPA will notify the reviewers when this occurs.

Below you will find a template for your comments. You are encouraged to use this template to facilitate the compilation of the peer review comments, but do not feel constrained by the format. You are free to revise as needed; this is just a starting point.

If a reviewer has questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If a reviewer has any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA's Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

Charge Questions:

(1) **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Examples might include: engine technology selection, battery SOC swing, accessory load assumptions, etc.) Please comment on any caveats or limitations that these inputs and parameters would affect the final results.

A. Baseline vehicle subsystem models/maps

- The development of baseline vehicle models with comparison of the model results to available 2010 EPA fuel economy test data was appropriate.

  - The models/maps for the subsystems used in these vehicle models were not provided in the report so that their adequacy could not be assessed.

  - Including these baseline models in the report would assist in assessing the development process as well as the adequacy of the new technology subsystem models/maps, which was not possible in this peer review.

  Recommendation: Since the baseline vehicles modeled were 2010 production vehicles, the models/maps for the subsystems used in these vehicle models should be included in the report before it is released.

- A major omission was that a baseline model of a hybrid vehicle, which is significantly more complex than the baseline vehicle, was not developed and compared to available EPA fuel economy test data for production hybrid vehicles.

  Recommendation: A baseline model of a hybrid vehicle should be developed and compared to 2010 EPA fuel economy test data for production hybrid vehicles.

B. Engine technology selection

- The engine technologies selected for this study, listed in Table 5.1 (page 22), are appropriate, but are not all-inclusive of possible future engine technologies.

  - Setting the minimum per-cylinder volume at 0.225L and the minimum number of cylinders at 3 is appropriate. However, achieving customer acceptable NVH with 3 cylinder engines continues to be problematic.

  Issue: The description of the derivation of all of the engine models/maps was insufficient.

Issue: The technology "package definitions" precluded an examination of the individual effects of a variety of technologies such as a single stage turbocharger vs. series-sequential turbochargers.

Issue: There are many engine technologies that have potential for reduced GHG emissions that were not included in this study, such as:

- **Single stage turbocharged engines**
- **Diesel hybrids**
- **Biofueled spark ignition and diesel engines**
- **Natural gas fueled engines**
- **Other alternative fuel engines**
- **Charge depleting PHEV and EV**

- The feasibility of the following assumptions for the engines modeled should be re-examined as indicated below.

- None of the Stoichiometric DI Turbo engines listed as references by Ricardo limited the turbine inlet temperature to a value as low as the 950C limit in the Ricardo model (Ref 1, 2, 3). Reducing the turbine inlet temperature to reach this limit is expected to result in BMEP levels below the assumed 25-30 bar level in the model (which were obtained in the referenced engine with a turbine inlet temperature of 1025C).

- Turbocharger delays of the magnitude assumed in the model will result in significant driveability issues for engines that are downsized approximately 50%. Although Ricardo assumed a turbocharger delay of approximately 1.5 seconds, the comparable delay published for a research engine was significantly longer at 2.5 seconds (Ref 3).

Transmission technology selection

- The transmission technologies selected for this study, listed in Table 5.3 (page 23) are appropriate.

- The forecast that current 4-6 speed automatic transmissions will have 7-8 speeds by 2020-2025 is appropriate for all except the smallest and/or low cost vehicles (page 19).

- The report mentions that the transmissions include dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants (page 22).

Recommendation: The detailed assumptions showing how the benefits of dry sump, improved component efficiency, improved

kinematic design, super finish, and advanced driveline lubricants were added to the transmission maps should be added to the report before it is released.

C. Hybrid technology selection

- The hybrid technologies selected for this study, listed in Table 5.2 (page 22) are appropriate.

Issue: The adequacy of the P2 Parallel and PS Power Split Hybrid systems cannot be determined without having, at a minimum, schematics and operational characteristics of the each system together with comparisons with today's hybrid systems.

- Although not contained in the report, the teleconference call with Jeff Cherry (EPA) on May 5, 2011 revealed that 90% of the deceleration kinetic energy would be recovered.

Kinetic energy recovery is limited by the following:

- Maintaining high generator efficiency over the range of speeds and resistive torques encountered during deceleration
- Limitations on the rate at which energy can be stored in the battery
- Losses in the power electronics
- Some energy is lost when energy is withdrawn from the battery for delivery to the motor.
- Inefficiencies in the motor at the speeds and torques required.

The inefficiencies of each of these four subsystems are in series and are compounded. If each subsystem had 90% efficiency, the kinetic energy recovery efficiency would be only 66%.

Issue: Capturing 90% of the deceleration kinetic energy is a significantly goal. The technology to be used to achieve this goal needs to be explained and appropriate references added to the report.

D. Actual models/maps for subsystems (engine, transmission, hybrid system, accessories, final drive, tires and vehicle)

- None of the subsystem models/maps were provided for review so comments on their adequacy are not possible.

Issue: Insufficient reasons are presented to justify why the models/maps for subsystems are not provided in the report, especially when one of the goals of the report was to provide transparency (per Jeff Cherry, May 5, 2011 teleconference and Item 5, below).

Recommendation: Subsystem models/map should be added to this report and another peer review conducted to assess their adequacy before this report is released.

Recommendation: To establish the adequacy of the subsystem models/maps, derivation details should be provided.

E. Accessory load assumptions

- The accessory selections listed in Table 5-2 (page 22) appear to be adequate except for the following issue:

Issue: Belt driven air conditioning for the stop-start powertrain configuration is not acceptable for driver comfort. Electrically driven air conditioning is required for the stop-start powertrain configuration to provide driver comfort for extended idle periods.

– Input values

- Alternator efficiency was increased from the current level of 55% to 70% to reflect "an improved efficiency design" (page 26 and 27).

Comment: Justification for the increase in alternator efficiency from 55% to 70% should be added to the report with references provided. Alternator efficiency as a function of speed and load may be more appropriate than a constant value.

- Accessory power requirements were not provided, such as shown in Figure 3-3 of Reference 4, for example.

Recommendation: Both mechanically driven and electrically driven accessory power requirements should be clearly provided in the report.

F. Battery SOC swing and SOC

- Although not contained in the report, an email from Jeff Cherry (EPA) on May 5, 2011 revealed that the SOC swing was 30% SOC to 70% SOC or 40% total, which appears to be appropriate.

- Achieving neutral SOC (neither net accumulation or depletion) for hybrid vehicle simulations is appropriate (page 30).

G. DOE ranges

- The following DOE ranges for Baseline and Conventional Stop-Start (page 23) appear to be appropriate, with the exception of Engine Displacement, as discussed below.

Parameter	DoE Range (%)	
Engine Displacement	50	125
Final Drive Ratio	75	125
Rolling Resistance	70	100
Aerodynamic Drag	70	100
Mass	60	120

Since the default for the Stoichiometric DI Turbo engine appears to be greater than 50% reduction in displacement (Standard Car baseline of 2.4L is reduced to 1.04L for the Stoichiometric DI Turbo (page 46)), the opportunity should be provided to start with a displacment near the baseline engine (2.4L) and progressively decrease it to approximatly 50% (1.04L). This would require an Engine Displacement upper range of over 200%. The model should also have the capabilty of increasing the boost pressure as the displacement is reduced.

- The following DOE ranges for P2 and PS hybrid vehicles (page 24) appear to be appropriate:

	DoE Range (%)			
Parameter	P2 Hybrid		Powersplit	
Engine Displacement	50	150	50	125
Final Drive Ratio	75	125	75	125
Rolling Resistance	70	100	70	100
Aerodynamic Drag	70	100	70	100
Mass	60	120	60	120
Electric Machine Size	50	300	50	150

H. Other inputs

- The Design Space Query within the Data Visualization Tool allows the user to set a continuous range of variables within the design space range. Although this capability is useful for parametric studies, the following risks are incurred with some of the variables.

  - The sliders for “Eng. Eff” and “Driveline Eff.” would allow the user to arbitrarily change engine efficiency or driveline efficiency uniformly over the map without having a technical basis for such changes.

  - The slider for weight would allow the user to add hybrid or diesel engines with signficant weight increases without incurring any vehicle weight increase.

Recommendation: A default weight increase/decrease should be added for each technology. If weight reductions are to be studied, then the user should have to input a specific design change, with the appropriate weight reduction built into the model, rather that having an arbitrary slider for weight.

(2) **Simulation methodology.** Please comment on the validity and applicability of the methodologies used in simulating these technologies with respect to the entire vehicle. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations. Does the model handle synergistic affects of applying various technologies together?

Concern: Methodologies used in simulating the subsystems and the overall vehicles were not provided, so that the validity and applicability of these methodologies cannot be assessed.

A. Major deficiencies in the report

- An overall schematic and description of the powertrain and vehicle models and the associated subsystem models/maps were not provided. Only vague descriptions were included in the text of the report.

- Technical descriptions of how the subsystems and vehicle models/maps for the baseline vehicles were developed were not provided.

- Most importantly, only non-technical descriptions of how each of the advanced technology subsystem models/maps was developed were provided.

- Descriptions of the algorithms used for engine control, transmission control, hybrid system control, and accessory control were not provided.

- Descriptions of how synergistic effects were handled were not provided.

B. Baseline vehicle model validation results

Ricardo developed baseline vehicle simulations for 2010 vehicles for which EPA fuel economy data were available (page 30). “For the 2010 baseline vehicles, the engine fueling maps and related parameters were developed for each specific baseline exemplar vehicle.” (page 25). Even though these are production vehicles, the models and maps used were not described (including whether they were derived from actual measurements or models) and they were not provided in the report so that their appropriateness could not be assessed.

Table 7.1 shows the calculated vs. EPA test data for the baseline vehicle fuel economy performance. This table should include percentage variation of the model calculations vs. the test data. The agreement of the model with the test data is within 11%, but this is a larger error than some of the incremental changes shown in Appendix 3. A closer agreement would have been expected.

> **Recommendation: A closer examination of the reasons for the up to 11% discrepancies between the models and baseline vehicles’ EPA fuel economy test data should be undertaken so that the models could be refined to provide better agreement.**

C. Transmission optimization

A transmission shift optimization strategy is presented in the report and the results are shown in Figure 6.1 (page 28). This figure shows very frequent shifting, especially for 4th, 5th and 6th gears.

> **Issue: Optimized shift strategies of the type used by Ricardo have been previously evaluated and found to provide customer complaints of "shift busyness". Customers are likely to reject such a shift strategy.**

D. Vehicle model issues

Although the report described the major powertrain subsystems included in the vehicle models (page 24), a description of the vehicle model was not provided.

> **Issue: A description of how aerodynamic losses, tire rolling losses and weight are handled in the model was not provided.**

E. Additional discussion of deficiencies is contained in Section 6, Other Comments.

(3) **Results**. Please comment on the validity and applicability of the results to the light-duty vehicle fleet in the 2020-2025 timeframe. Please comment on any apparent unstated or implicit assumptions that may affect the results, and on any related caveats or limitations.

A. Overview of results

The results from this work could be useful in evaluating possible GHG emission reductions in the 2020-2025 timeframe if the issues throughout this peer review were addressed and the recommendations in Item 5 (below) were implemented. However, even if the foregoing deficiencies were resolved, the foregoing caveat that there are numerous technologies that have potential for reduced GHG emissions that were not included in this study must be recognized (see Item 1B, above).

B. Sample runs of CSM

In the review process, several sample runs of the Complex Systems Model (CSM) for the Standard Car (Toyota Camry) were made and the results are shown in the attached chart (at the end of this peer review) and summarized below.

- Baseline engine with AT6-2010 to Stoichiometric DI Turbo, Stop-Start, AT8-2020
    - 38.7% improvement in M-H mpg
    - Reference 3 identified a 25-30% improvement in mpg for a 50% downsized, DI, Turbo engine.
    - The remaining 9-14% potentially could be explained by stop-start and the change from AT6-2010 to AT8-2020 (although the details of the systems and the models used would be needed to make this assessment).

- AT8-2020 to DCT
    - 3.3% improvement in M-H mpg
    - This improvement appears reasonable.

- Stoichiometric DI Turbo with Stop-Start to P2 Hybrid
    - 18.2% improvement in M-H mpg
    - This improvement appears reasonable.

- Stoichiometric DI Turbo with Stop-Start to PS Hybrid
    - 11.1% improvement in M-H mpg
    - A detailed explanation of the differences in the improvements between the P2 and PS hybrids should be provided in the report, especially considering that the P2 hybrid has better fuel economy and uses a 70% smaller electric motor (24 vs. 80 kW).

- Stoichiometric DI Turbo PS Hybrid to Naturally Aspirated Atkinson CPS Hybrid
    - Loss of 2.3% M-H mpg (From Stoichiometric DI Turbo PS Hybrid)

- The details of the Naturally Aspirated Atkinson CPS Hybrid should be provided to explain the nearly equal fuel economy to the Stoichiometric DI Turbo PS Hybrid.

- Stoichiometric DI Turbo PS Hybrid to Naturally Aspirated Atkinson DVA Hybrid
    - 2.1% M-H mpg improvement in M-H mpg (From Stoichiometric DI Turbo PS Hybrid)
    - The details of the Naturally Aspirated Atkinson DVA Hybrid should be provided to explain the nearly equal fuel economy to the Stoichiometric DI Turbo PS Hybrid

C. Issue with CSM

Issue: The technology "package definitions" (page 22 and 23) precluded an examination of the individual effects of a variety of technologies.

Some examples where the model did not allow a build up of comparison cases are:

- Baseline engine with AT-2010 to AT-2020 to DCT
- Baseline engine without stop-start to with/stop-start

D. Other issues:

- The Advanced Diesel does not appear to be modeled for the Standard Car and Small MPV (page 46 and 47), yet no reason was provided.

- The P2 and PS hybrid system was not modeled for the LHDT (page 47), yet no reason was provided.

- When the baseline cases were run in the Complex Systems Model, incorrect values of displacement and architecture were shown in the output.
    - o As an example shown on the attached chart (copied from the output of the CSM), the baseline for the Standard Car with a 2.4L engine shows a displacement of 1.04L.
    - o For the same example, the architecture is shown as "conventional SS", whereas the baseline was understood to not have the stop-start feature (page 22, Table 5-2).

(4) **Completeness.** Please comment on whether the report adequately describes the entire process used in the modeling work from input selection to results.

Concern: This report has significant deficiencies in its description of the entire process used in the modeling work. Many of these deficiencies have been previously discussed, but are listed here for completeness.

- An overall schematic and description of the powertrain and vehicle models and the associated subsystem models/maps were not provided. Only vague descriptions were included in the text of the report.

- Technical descriptions of how the subsystems and vehicle models/maps for the baseline vehicles were developed were not provided.

- None of the overall or subsystem models/maps were provided for review so comments on their adequacy are not possible.

- Most importantly, only minimal descriptions were provided of how each of the advanced technology subsystem models/maps was developed.

- Descriptions of the algorithms used for engine control, transmission control, hybrid system control, and accessory control were not provided.

- Descriptions of how synergistic effects were handled were not provided.

There are many engine technologies that have potential for reduced GHG emissions that were not included in this study, such as:

- **Single stage turbocharged engines**
- **Diesel hybrids**
- **Biofueled spark ignition and diesel engines**
- **Natural gas fueled engines**
- **Other alternative fuel engines**
- **Charge depleting PHEV and EV**

Additional discussion of completeness is contained in Item 6, Other Comments.

(5) **Recommendations.** Please comment on the overall adequacy of the report for predicting the effectiveness of these technologies, and on any improvements that might reasonably be adopted by the authors for improvement. Please note that the authors intend the report to be open to the community and transparent in the assumptions made and the methods of simulation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

This report needs major enhancements to reach the stated goal of being open and transparent in the assumptions made and the methods of simulation. Recommendations to rectify the deficiencies in these areas are provided in the previous four items.

A. Overall recommendations

Overall Recommendation: Provide all vehicle and powertrain models/maps and subsystem models/maps used in the analysis in the report so that they can be critically reviewed.

Overall Recommendation: Expand the technology "package definitions" to enable evaluation of the individual effects of a variety of technologies.

B. Specific recommendations for improvements

1. Provide an overall schematic and description of the powertrain and vehicle models.
    a. Show all of the subsystem models/maps used in the overall model.
    b. Show the format of the information in each of the subsystem models (including input, subsystem model, output).

2. Provide technical descriptions of how the subsystems and vehicle models/maps for the baseline vehicles were developed.

3. Provide overall system and subsystem models/maps in the report.

4. Provide detailed technical descriptions of how each of the advanced technology subsystem models/maps was developed.

5. Provide descriptions of the algorithms used for engine control, transmission control, hybrid system control, and accessory control.

6. Provide detailed descriptions of how synergistic effects were handled.

C. Additional recommendations shown in bold print throughout other sections of this report are repeated below for completeness (in the order that they appear in the report).

Recommendation: Since the baseline vehicles modeled were 2010 production vehicles, the models/maps for the subsystems used in these vehicle models should be included in the report before it is released.

Recommendation: A baseline model of a hybrid vehicle should be developed and compared to 2010 EPA fuel economy test data for production hybrid vehicles.

Recommendation: The detailed assumptions showing how the benefits of dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants were added to the transmission maps should be added to the report before it is released.

Recommendation: Subsystem models/map should be added to this report and another peer review conducted to assess their adequacy before this report is released.

Recommendation: To establish the adequacy of the subsystem models/maps, derivation details should be provided.

Recommendation: Both mechanically driven and electrically driven accessory power requirements should be clearly provided in the report.

Recommendation: A default weight increase/decrease should be added for each technology. If weight reductions are to be studied, then the user should have to input a specific design change, with the appropriate weight reduction built into the model, rather that having an arbitrary slider for weight.

Recommendation: A closer examination of the reasons for the up to 11% discrepancies between the models and baseline vehicles' fuel economy test data should be undertaken so that the models could be refined to provide better agreement.

D. There are numerous "Issues" identified throughout this peer review that need to be addressed with specific resolution actions.

(6) **Other comments**. Please provide your comments on report topics not otherwise captured by the aforementioned charge questions.

Overview

The vehicle model and powertrain model were developed and implemented by Ricardo in the MSC.Easy5 software package. The model reacts to driver input to provide the torque levels and wheel speeds required to drive a specified vehicle over specified driving cycles. The overall model consists of subsystem models that determine key component outputs such as torque, speeds, heat rejection, and efficiencies. Subsystem models are expected to be required for the engine, accessories, transmission, hybrid system (if included), final drive, tires and vehicle, although the report did not clearly specify the individual subsystem models used.

A design of experiments (DOE) matrix was constructed and the vehicle models were used to generate selected performance, fuel economy and GHG emission results over the design space of the DOE matrix. Response surface modeling (RSM) was generated in the form of neural networks. The output from each model simulation run was used to develop the main output factors used in the fit of the RSM. The resulting Complex Systems Model (CSM) provides a useful tool for viewing the results from this analysis that included over 350,000 individual vehicle simulation cases.

Overall Issue:

The vehicle and powertrain models/maps and subsystem models/maps used in the analysis were not provided in the report and could not be reviewed. In most cases, the report stated that the models/maps were either proprietary to Ricardo or at least elements were proprietary so that they could not be provided for review. Without having these models/maps and subsystem models/maps, their adequacy and suitability cannot be assessed.

Overall Recommendation: Provide all vehicle and powertrain models/maps and subsystem models/maps used in the analysis in the report so that they can be critically reviewed.

Overall Issue:

The technology "package definitions" preclude an examination of the individual effects of a variety of technologies. For example, for the Stoichiometric DI Turbo engine, only the version with a series-sequential turbocharger could be evaluated whereas a lower cost alternative with a single turbocharger could not be evaluated. Likewise, only the AT8-2020 transmission could be evaluated with the Stoichiometric DI Turbo engine, while the substitution of the AT6-2010, as a lower cost alternative, could not be evaluated.

Overall Recommendation: Expand the technology "package definitions" to enable evaluation of the individual effects of a variety of technologies.

This section provides additional details regarding the overall issues and comments made in the foregoing five items.

Engine Models

Engine models provided the torque curve, fueling map and other input parameters (which were not specified in the report) (page 25). Since the report stated that "The fueling maps and other engine model parameters used in the study were based on published data and Ricardo proprietary data" (page 26), their adequacy and suitability could not be assessed.

The report states that engines used in the model were developed using two main methods (page 14).

1. The first method assumed that "reported performance of current research engines" would closely resemble production engines of the 2020-2025 timeframe.
2. The second method began with current production engines and then a "pathway of technology improvements over the new 10-15 years that would lead to an appropriate engine configuration for the 2020-2025 timeframe" was applied.

Both of these approaches are reasonable if:

1. appropriate references are provided,
2. the reported performances for the research engines used are documented in the report,
3. the technology improvements are documented in the report, and
4. the methodology of incorporating the improvements is fully documented.

The description of the derivation of the engine models in the report was, at best, vague, as illustrated by the two examples below:

Example 1: Stoichiometric DI Turbo
The current research engines of this configuration were reported to be the Sabre engine developed by Lotus and the downsized concept engine developed by Mahle. Since the engine modeled in the Ricardo report had a peak BMEP of 25-30 bar and used series-sequential turbochargers, the Sabre engine is not applicable since it only had a peak BMEP of 20 bar and used a single stage turbocharger (Refs 1 and 2).

On the other hand, the Mahle engine appeared to be directly applicable, since it had a peak BMEP of 30 bar and used series-sequential turbocharging (Ref 3). Since Reference 3 provided the BSFC map for this engine, shown below, it is not clear why the Ricardo report could not have shown this map, or a map derived from this one, and then described how it was derived and/or combined with other maps to provide the model used in the report.

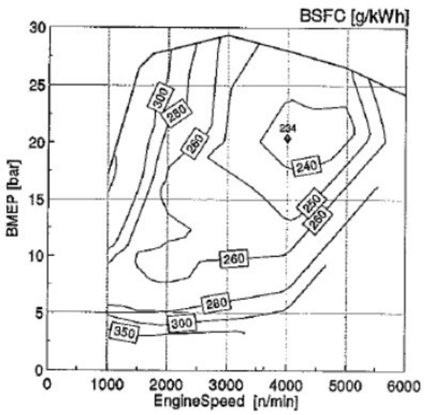

Figure 19: BSFC over the engine operating envelope, CR 9.7:1.

Example 2: Advanced Diesel
For the advanced diesel, the report provided the following description: "…the LHDT engine torque curve and fueling maps were generated by starting with a 6.6L diesel engine typical for this class and applying the benefits of improvements in pumping losses or friction to the fueling map". No description of the improvements in pumping losses or friction reduction was provided and the variation of these improvements over the speed and load map were not provided. In addition, the baseline 6.6L engine map was not provided, the 6.6L friction map was not provided and the methodology for applying the improvements to the 6.6L engine map was not provided.

The report should explain whether the engine model is only a map of BSFC vs. speed and load, or if the engine model includes details of the turbocharger, valve timing, and control algorithms for parameters such as air/fuel ratio, spark/injection timing, EGR rate, boost pressure, and valve timing.

Advanced valvetrains were included in many of the advanced engines (page 12). However, the method for applying these advanced valvetrains to the engine maps was not provided. Also, no description of the control strategy for these valvetrains was provided. The report did not provide a description of how the reduction of pumping losses with an advanced valvetrain was applied to a downsized engine that already had reduced pumping losses. Therefore, no assessment of how the model handled synergies could be made.

In summary, the Ricardo report provided insufficient descriptions of the derivation of the maps used for all of the engines in this study, which included:

- Baseline
- Stoichiometric DI Turbo
- Lean-Stoichiometric Switching
- EGR DI Turbo
- Atkinson Cycle
- Advanced Diesel

Transmission Models

Similar to engine models, the description of the derivation of transmission models was also vague. Using the automatic transmission model as an example, “For the 2020-2025 timeframe, losses in automatic transmissions are expected to be about 20-33% lower than in current automatic transmissions from the specific technologies described below.” The specific technologies that could provide these reductions appeared to include:

- Shift clutch technology - to improve thermal capacity of the shifting clutch to reduce plate count and lower clutch losses during shifting.
- Improved kinematic design – no description of these improvements was provided.
- Dry sump – to reduce windage and churning losses.
- Efficient components – improvements in seals, bearings and clutches to reduce drag.
- Super finishing - improvements expected were not specified.
- Lubrication- new developments in base oils and additive packages, but improvements were not specified.

In addition to not specifying the improvements expected from these technologies, no indication was provided of how these technologies were applied to the transmission models. For example,

- The report stated that losses in automatic transmissions are expected to be about 20-33% lower than in current automatic transmissions (page 19). However, the baseline losses were not provided for reference and the means to achieve these reductions were not described.
- The report stated that energy losses in DCTs are expected to be 40-50% lower than in current automatic transmissions (page 19). The details of this reduction were not provided and references describing these reductions were not provided.
- Bearing and seal losses have a greater effect on efficiency at light loads than at heavy loads. The report did not describe how these losses were incorporated in the model. In contrast to the lack of descriptions of details in the report, Reference 4, as an example, provided the following map of bearing losses in a transmission as a function of shaft diameter and speed. Similar details for the relevant aspects of the transmission models in this report would have been expected.

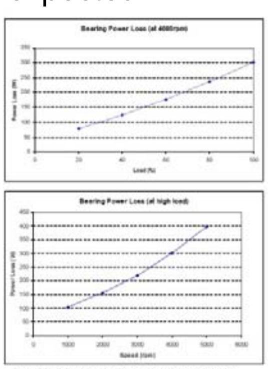

Figure 5-23: Estimated power loss in a deep-groove ball bearing

In summary, the Ricardo report provided insufficient descriptions of the derivation of the maps for the following transmissions:

- Advanced automatic
- Dry clutch DCT
- Wet clutch DCT
- P2 Parallel hybrid transmission
- PS Power Split hybrid transmission

In addition, the models for the automatic transmissions of the baseline vehicles were not provided, so that their adequacy could not be assessed.

Hybrid Technologies Models

Key elements of a hybrid system include: electric machines (motor-generator), power electronics, and a high-voltage battery. Only the following vague description of the models for these subsystems was provided: “For each of these systems, current state of the art technologies were adapted to an advanced 2020-2025 version of the systems, such as by lowering internal resistance in the battery pack to represent 2010 chemistries under development and decreasing losses in the electric machine and power electronics to represent continued improvements in technology and implementation” (page 29). This vague description did not provide adequate details to assess the adequacy of these models. For example, specific values for internal resistance with references should be provided together with an illustration of how this was incorporated in the model of the battery.

In contrast, as an example, Reference 6 provided a detailed motor efficiency map, shown below, as well as efficiency maps of other key components of the Prius hybrid vehicle. Similar maps for all hybrid subsystems would be expected in this report.

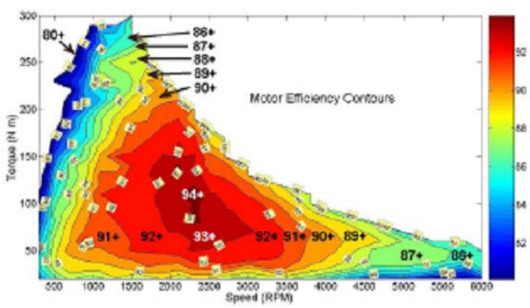

Fig. 3.18. 2004 Prius motor efficiency contour map.

In addition, “a Ricardo proprietary methodology was used to identify the best possible fuel consumption for a given hybrid powertrain configuration over the drive cycles of interest.” (page 29), which precluded an assessment of its suitability.

No mention was provided of how the cooling system for the hybrid system was modeled.

Accessory Models

None of the accessory models were not provided for review, so their adequacy and suitability cannot be assessed.

The accessory loads vs. engine speed for the conventional belt driven accessories were apparently removed from the engine when electric accessories were applied. However, the conventional accessory loads as well as the alternator loads/battery loads for the electric accessories were not provided.

In contrast, as an example, Reference 4 provided the following map of an electric water pump and AC compressor drive efficiency. Similar maps for all accessory models would be expected in this report.

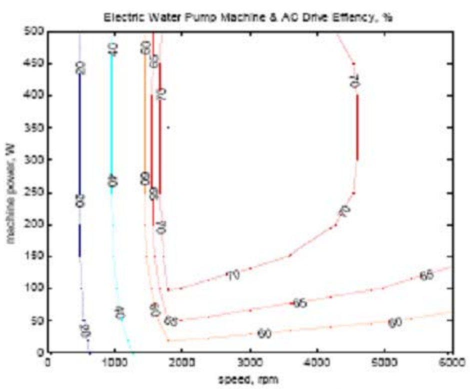

Figure 3-6: Electric Water Pump Machine & Air Conditioning Drive Efficiency

Boosting Systems

The report states that “various boosting approaches are possible, such as superchargers, turbochargers, and electric motor-driven compressors and turbines.” (page 13). However, elsewhere the report states “series-sequential turbochargers” will be used on the Stoichiometric DI Turbo engine (page 15).

It is not clear in the report how the series-sequential turbocharger was selected from the variety of boosting devices that were introduced. Models for the turbochargers with compressor and turbine efficiency maps were not provided, so the appropriateness of these model cannot be assessed.

> **Comment: The model should include a single turbocharger system with less extreme downsizing as advocated by the Sabre Engine (References 1 and 2) as a lower cost alternative to series-sequential turbochargers.**

Stoichiometric DI Turbo Engine

The table below compares several attributes of the Ricardo Stoichiometric DI Turbo Engine with the Mahle Turbocharged, DI Concept Engine.

Feature	Ricardo Stoichiometric DI Turbo Engine	Mahle Turbocharged, DI Concept Engine SAE 2009-01-1503
Downsizing	57% (for Std Car)	50%
BMEP	25-30 bar	30 bar
Turbo Response	1.5 second time constant	2.5 second time constant (estimated from 4 second total response time)
Turbine Inlet Temperature	950C	1025C
NEDC fuel economy	Not available	25 – 30% better that NA baseline

Key content of the Mahle Turbocharged, DI Concept Engine:
- Two turbochargers in series
- Charge air cooler
- Dual variable valve timing
- High energy ignition coils
- Fabricated, sodium cooled valves
- EGR cooler

Reference 3 describing the Mahle concept engine stated that lowest fuel consumption that usually occurs around 2000 rpm had moved out to 4000 rpm for the series-sequential turbocharged engine.

> **Issue: The Ricardo report did not discuss the concern that the lowest fuel consumption in a series-sequential turbocharged engine had moved out to 4000 rpm, rather than the usual 2000 rpm and did not discuss how this concern was handled.**

The foregoing table indicates several significant issues:

1. The turbine inlet temperature of the Mahle engine is significantly higher than the limit assumed for the Ricardo engine (1025C vs. 950C). Reducing the turbine inlet temperature is expected to result in lower BMEP levels where the temperature is limited.

2. The turbocharger response time for the Mahle engine is 2.5 seconds, whereas Ricardo assumed a time constant of 1.5 seconds. Such turbocharger delays are expected to result in significant driveability issues for engines that are downsized approximately 50%.

The table below compares several attributes of the Ricardo Stoichiometric DI Turbo Engine with the Lotus Sabre Engine.

Feature	Ricardo Stoichiometric DI Turbo Engine	Lotus Sabre Engine SAE 2008-01-0138
Downsizing	57% (for Std Car)	32%
BMEP	25 - 30 bar	20.1 bar
Turbine Inlet Temperature	950C	980C 1050C (common) and desired
Fuel RON	87 PON (Pump Octane Number)	95 RON Est 91 PON

The paper on the Sabre engine (Reference 2) indicates that operation at lower turbine inlet temperatures results in a reduction in BMEP. However, the turbine inlet temperature for the Sabre engine is still 40C above Ricardo's assumption.

Reference 2 indicates that the Sabre engine with a single stage turbocharger provides an attractive alternative to extreme downsizing with series-sequential turbochargers.

Cooled Exhaust Manifold

The Ricardo report states, "The future engine configuration was assumed to use a cooled exhaust manifold to keep the turbine inlet temperature below 950C…" No explanation was provided of how the limit on turbine inlet temperature would affect boost pressure and power.

Warm-Up Methodology

"Ricardo used company proprietary data to develop an engine warm-up profile" which was used to increase the fueling requirements during the cold start portion of the FTP75 drive cycle (page 26). Since this data was proprietary, no assessment of its appropriateness can be made.

Elsewhere the report states, "A bag 1 correction factor is applied to the simulated "hot" fuel economy result of the vehicles to approximate warm-up conditions…" The correction factor reduces the fuel economy results of the FTP75 bag 1 portion of the drive cycle by 20% on the current baseline vehicles and 10% on 2020-2025 vehicles that take advantage of fast warm-up technologies" (page 29). No references or data are cited to support this significant reduction in correction factor.

> **Issue: No explanation was provided to clarify when the "engine warm-up profile" is used and when the "correction factor" is used. Therefore, the appropriateness of the warm-up methodology cannot be assessed.**

Lean-Stoichiometric Switching Engine

The report states that this engine will use a lean NOx trap or a urea-based SCR system (page 15). The use of fuel as a reducing agent was also suggested in the report (page 16). However, the fuel economy penalty associated with regenerating the NOx trap or the reducing agent for the SCR system was not provided.

Engine Scaling

The report states, "The BSFC of the scaled engine map is …adjusted by a factor that accounts for the change in heat loss that comes with decreasing the cylinder volume, and thereby increasing the surface to volume ratio for the cylinder" (page 26). This is a directionally correct correction. However, specific values for the correction should be provided, together with references to the data and methodology used to derive the values used.

> **Issue: The report states, "…downsizing the engine directly scales the delivered torque, …" (page 26). However, since there will be increased heat loss from the smaller displacement cylinder, the torque would be expected to be less than the directly scaled values for the same fueling rate.**

References (Used for this Review that are also listed in the Report)

References used to establish the basis for the Stoichiometric DI Turbo engine assumptions (page 15 of the report):

1. Coltman, et al. (2008), “Project Sabre: A Close-Spaced Direct Injection 3-Cylinder Engine with Synergistic Technologies to Achieve Low CO2 Output”, SAE Paper 2008-01-0138
2. Turner, et al. (2009), ‘Sabre: A Cost-Effective Engine Technology Combination for High Efficiency, High Performance and Low CO2 Emissions”, IMechE conference proceedings
3. Lumsden, et al. (2009), “Development of a Turbocharged Direct Injection Downsizing Demonstrator Engine”, SAE Paper 2009-01-1503

Reference that summarizes the 2008 study by Perrin Quarles Associates (PQA) that provided the 2010 baseline cases for five LDV classes (Page 30 of the report):

4. PQA and Ricardo (2008), "A Study of Potential Effectiveness of Carbon Dioxide Reducing Vehicle Technologies"

References containing supporting information for the hybrid powertrains:

5. Hellenbroich, et al. (2009), "FEV's New Parallel Hybrid Transmission with Single Dry Clutch and Electric Torque Support"
6. Staunton, et al. (2006), "Evaluation of 2004 Toyota Prius Hybrid Electric Drive System", ORNL technical report TM-2006/423

Sample Output From Complex System Model (CSM)
5/4/2011
Relative Percentage Differences Were Added by W. R. Wade

	FTP	HWFET	US06	Combined	0-60 mph	Displacement	FDR	Rolling R.	Aero	Weight	Eng.Eff.	Hybrid	Class
CONVENTIONAL SS													
Base	30.0	43.5	29.1	34.9	8.3	1.04	3.23	0.00822	0.69	3625	1		Standard Car (Toyota Camry)
(Baseline)	-	-	-	-									
Stoich DI Turbo	44.5	54.2	32.5	48.4	8.5	1.04	3.23	0.00822	0.69	3625	1		Standard Car (Toyota Camry)
	48.2%	24.6%	11.7%	38.7%									
AT8-2020 to DCT	46.3	55.3	33.7	50.0	8.6	1.04	3.23	0.00822	0.69	3625	1		Standard Car (Toyota Camry)
	4.21%	1.93%	3.51%	3.28%									
HYBRIDS													
P2 w/Stoich DI Turbo	61.6	56.3	36.6	59.1	8.6	0.83	3.23	0.00822	0.69	3625	1	24	Standard Car (Toyota Camry)
(Rel to Conv SS SCT)	32.96%	1.80%	8.89%	18.23%									
PS w/Stoich DI Turbo	57.5	53.3	36.4	55.5	9.2	0.83	3.23	0.00822	0.69	3625	1	80	Standard Car (Toyota Camry)
(Rel to Conv SS DCT)	24.00%	-3.50%	8.24%	11.11%									
PS w/Atkinson CPS	55.1	53.2	38.1	54.3	8.5	2.4	3.23	0.00822	0.69	3625	1	80	Standard Car (Toyota Camry)
(Rel to Stoich DI Turbo)	-4.08%	-0.18%	4.61%	-2.29%									
PS w/Atkinson DVA	58.3	54.8	38.7	56.7	8.5	2.4	3.23	0.00822	0.69	3625	1	80	Standard Car (Toyota Camry)
(Rel to Stoich DI Turbo)	1.5%	2.7%	6.1%	2.1%									

Appendix D. Peer Reviewer Comments as Submitted, Round 2

Peer review of the report, “Computer Simulation of Light-Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe”

Report by:Scott McBroom

Date of Report: 8/17/1

Charge to Peer Reviewers:

As EPA and NHTSA develop programs to reduce greenhouse gas (GHG) emissions and increase fuel economy of light-duty highway vehicles, there is a need to evaluate the effectiveness of technologies necessary to bring about such improvements. Some potential technology paths that manufacturers might pursue to meet future standards may include advanced engines, hybrid electric systems, mass reduction, along with additional road load reductions and accessory improvements.

Ricardo Inc. has developed simulation models including many of these technologies with the inputs, modeling techniques, and results described in the Ricardo Inc. document that you have been provided dated March 10, 2011.

EPA is seeking the reviewers' expert opinion on the inputs, methodologies, and results described in this document and their applicability in the 2020-2025 timeframe. The Ricardo Inc. report is provided for review. We ask that each reviewer comment on all aspects of the Ricardo Inc. report. Findings of this peer review may be used toward validation and improvement of the report and to inform EPA and NHTSA staff on potential use of the report for predicting the effectiveness of these technologies. No independent data analysis will be required for this review.

Reviewers are asked to orient their comments toward the five (5) general areas listed below. Reviewers are expected to identify additional topics or depart from these general areas as necessary to best apply their particular set of expertise toward review of the report.

Comments should be sufficiently clear and detailed to allow readers familiar with the report to thoroughly understand their relevance to the material provided for review. EPA requests that the reviewers not release the peer review materials or their comments until Ricardo Inc. makes its report and supporting documentation public. EPA will notify the reviewers when this occurs.

Below you will find a template for your comments. You are encouraged to use this template to facilitate the compilation of the peer review comments, but do not feel constrained by the format. You are free to revise as needed; this is just a starting point.

If a reviewer has questions about what is required in order to complete this review or needs additional background material, please contact Susan Blaine at ICF International (SBlaine@icfi.com or 703-225-2471). If a reviewer has any questions about the EPA peer review process itself, please contact Ms. Ruth Schenk in EPA’s Quality Office, National Vehicle and Fuel Emissions Laboratory by phone (734-214-4017) or through e-mail (schenk.ruth@epa.gov).

Scott McBroom

Charge Questions:

(1) **Inputs and Parameters.** Please comment on the adequacy of numerical inputs to the model as represented by default values, fixed values, and user-specifiable parameters. Examples might include: engine technology selection, battery SOC swing, accessory load assumptions, etc.) Please comment on any caveats or limitations that these inputs and parameters would affect the final results.

Battery Model: Overall the battery model is sound; however, I don't understand why cold modeling is included. The FTP testing doesn't include cold testing therefore only 25C and up should be included and the battery is consistent at those temps.

Engine Model:
I see data on the HEDGE engine technology but no mention of it in the list of engine technologies unless it's the high EGR DI gasoline engine.

Engine Model:
The trend in engine technology is forced induction (engine downsizing). I think the selection of turbo only is too limiting. I anticipate variable speed supercharging and other combination of forced induction. I think the study would do well to include this.

Rgen Alternator:
Ricardo states - 70% efficient alternator; however, alternator efficiency is a function of temp, speed and load. 70% is probably the best, but it's highly unlikely that it will operate there for the duration of the conditions.

Diesel Engine Fuel Maps:
The presentation shows the technologies to be deployed, but doesn't discuss how the 2020 bsfc maps were arrived at. It might be helpful to also use the same method for comparison that the authors used to show LBDI vs EGR

Diesel Technology:
Curious about the author's comment regarding supercharging, "advances to avoid variable speed". Why not variable speed?

Curious about why no discussion of advanced materials in engines to achieve improvements.

EBDI Engine:
Couldn't find fuel economy benefit discussion in presentation. Should be done as gasoline or energy equivalent. I know CO2 is proportional, but….

Future Developments in Engine Friction –
I think it would be worthwhile to point out that there are technologies that are more driven by increased durability rather than fuel economy but they could play off one another. Engine friction reduction is one of those areas.

(2) **Simulation methodology.** Please comment on the validity and applicability of the methodologies used in simulating these technologies with respect to the entire vehicle. Please comment on any apparent unstated or implicit assumptions and related caveats or limitations. Does the model handle synergistic affects of applying various technologies together?

Transmission Model:
Ricardo describes an approach that asserts that using an average efficiency value vs a 3D efficiency map yields insignificant differences over the CAFÉ drive cycles, but offers no results to validate the claim.

Transmission Model:
Ricardo offers no discussion of how inertial changes are managed during shifts. This may have greatest impact on the shift strategies where the transmission shifts to put the engine at the best bsfc for the given load.

Hybrid:
I don’t see any effort to model motor/inverter temperature effects. One would expect significant degradation of motor capability as things heat up during normal operation.

Regen Alternator:
Alternator model is too simplistic. On average the efficiency is too high as identified and it’s unrealistic to assume that the battery will be able to accept 100% of the charge.

EHVA:
The paper addresses the potential of the technology nicely. Since it was published in 2003 has any more recent work been done to address the durability and issues brought up in the conclusions?

Accessories:
I don’t see any discussion on the treatment of accessories. I believe from my review of the previous material, that the authors assume that all accessories will be electric. I think that engine driven accessories will play a key role in 2020.

(3) **Results**. Please comment on the validity and applicability of the results to the light-duty vehicle fleet in the 2020-2025 timeframe. Please comment on any apparent unstated or implicit assumptions that may affect the results, and on any related caveats or limitations.

Motor Efficiency Maps
I am having trouble believing that motor efficiency will stay above 90% once temperature effects are accounted for. It also seems to me that these numbers don't include the inverter even though the authors say that it does. The UQM maps seem more reasonable. As stated in a previous comment, I believe that the cost reductions needed for motors will drop their efficiencies in the future.

After reading the papers and presentations I come to the assumption that the papers were used to guide the selection of technology, but it's not clear which maps were generated from model and which maps were generated in the test cell. It's evident that there is a heavy concentration on engine technology and the fidelity of the engine models, which is appropriate. I have a slight concern about the impression I'm left with; that there is not much attention to the interaction of systems effects. This is most likely because of cost and availability of data. I would like to see the EPA articulate a process for looking at system interactions, continuous improvement and model compatibility. For example if the study were to run over several years the researches should feel confident comparing a result generated with the models in 2013 to modeling results generated today.

(4) **Completeness.** Please comment on whether the report adequately describes the entire process used in the modeling work from input selection to results.

Hybrid:
Ricardo asserts that electric machine design activities of the future will most like concentrate around cost reductions; however I see machine efficiency dropping in order to meet cost reductions. Therefore I think it premature to assume that efficiency will stay the same and cost will drop.

(5) **Recommendations.** Please comment on the overall adequacy of the report for predicting the effectiveness of these technologies, and on any improvements that might reasonably be adopted by the authors for improvement. Please note that the authors intend the report to be open to the community and transparent in the assumptions made and the methods of simulation. Therefore recommendations for clearly defined improvements that would utilize publicly available information would be preferred over those that would make use of proprietary information.

(6) **Other comments**. Please provide your comments on report topics not otherwise captured by the aforementioned charge questions.

PEER REVIEW:

Computer Simulation of Light-Duty Vehicle Technology for Greenhouse Gas Emission Reduction in the 2020-2025 Timeframe

Review Conducted for:

U.S. EPA

Review Conducted By:

Shawn Midlam-Mohler

Review Period:

4/28/2011 – 5/16/2011

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Executive Summary

For the purpose of describing the modeling approach used in the forecasting of the performance of future technologies, the report reviewed is inadequate. In virtually every area, the report lacks sufficient information to answer the charge questions provided for the reviewer. It is entirely possible that the approach used is satisfactory for the intended purpose. However, given the information provided for the review, it is not possible for this reviewer to make any statement regarding the suitability of this approach. Some brief comments on each of the five charge questions are provided below:

Inputs and Parameters – From a high level, it is clear what the inputs to the design space tool are, which are listed in tables 8.1 and 8.2. At the next level down (i.e. the vehicle and subsystem models) there is no comprehensive handling of inputs in parameters in the report. Some models are partially fleshed out in this area but most are lacking. By way of example, the engine models are described as maps which are "defined by their torque curve, fueling map, and other input parameters" where "other input parameters" are never defined.

Simulation Methodology – The vehicle model is reported as "a complete, physics-based vehicle and powertrain system model" - which it is not. The modeling approach used relies heavily on maps and empirically determined data which is decidedly not physics-based. This nomenclature issue aside, the model is not described in sufficient detail in the report to make an assessment in this area. An excellent example of this is the electric traction drives and HEV energy storage system for which the report mentions no details, even qualitative ones, on the structure of the models.

Results - The third charge questions deals with the validity and the applicability of the resulting prediction. The difficulty in this task is that it is an extrapolation from present technology that uses an extrapolation method (*i.e.* the model) and a set of inputs to the model (*i.e.* future powertrain data.) Since it is not possible to validate the results against vehicles and technology that do not exist, one can only ensure that the model and the model inputs are appropriate for the task. Because of the lack of transparency in the model and inputs it is difficult to make any claims regarding the results. In trying to validate results, one example is cited in the body of the report that shows the baseline engine getting superior HWFET and US06 fuel economy than all of the other non-HEV powertrains with other factors being the same – this leaves some skepticism regarding the results.

Completeness – Based on the above, it is clear that this reviewer feels the report is inadequate at describing the entire process of modeling work from input selection to results. There was not a single subsystem that was documented at the level desired. It is understood that, in some cases, there are things of a proprietary nature that must be concealed. As a trivial example, the frontal area of the vehicle classes does not seem to be anywhere in the report or data analysis tool. This is one parameter amongst hundreds excluding the real details of the models (*i.e.* equations or block diagrams), methods used to generate engine maps, details on control laws, *etc.* On the topic of proprietary data, there are many ways of obscuring data sufficiently that can demonstrate a key point (i.e. simulation accuracy) without compromising confidentiality of data – this should not be a major barrier to providing some insight into the inner working of the simulator.

Recommendations – Given the low level of detail given in the report, it does seem that the strategy used is consistent with the goal of the work and what others in the field are doing. That being said, the report is inadequate in nearly every respect at documenting model inputs, model parameters, modeling methodology, and the sources and techniques used to develop the technology performance data. Given the need for transparency in this effort, this reviewer feels that the detail in the report is wholly inadequate to document the process used. *The organization responsible for the modeling has expertise in this area it is certainly possible that the methodology is sound, however, given just the information in the report there is simply no way for an external reviewer to make this conclusion.*

Because of the lack of hard information to answer the charge questions, this peer review evolved mainly into a suggested list of details that should be brought forward in order to allow the charge questions to be answered properly. With this information, it is hoped that a person with expertise in the appropriate areas will be able comment on the work more fully.

Simulation Methodology

The simulation methodology is generally not described in the report in sufficient detail to assess the validity and accuracy of the approach. The models and approach are described qualitatively; however, this is insufficient to truly evaluate the ability of the modeling approach to perform the desired function. The following subsections address specific issues with the models, inputs, and parameters and suggest possible corrective actions to address these issues.

Vehicle Model

The vehicle model is described as "a complete, physics-based vehicle and powertrain system model" developed in the MSC.Easy5™ simulation environment. This description is not particularly helpful in defining the type of model as portions of the model are clearly not physics based, such as the various empirical maps used or sub-models like the warm-up model which is by necessity an empirical model due to the complexity of the warm-up process compared to the expected level of fidelity of the model. It is assumed that a standard longitudinal model accounts for rolling losses, aero losses, and grade is used to model the forces acting on the vehicle. Input parameters for the vehicle model are not described. The baseline vehicle platforms are listed, however, the relevant loss coefficients are not provided (rolling resistance, drag coefficient, inertia.)

Suggested Corrective Action:

1. List the dynamic equation describing the longitudinal motion of the vehicle
    a. NOT ADDRESSED IN SUPPLEMNTAL MATERIAL REVIEWED
2. List all parameters used for each vehicle class for simulation
    a. NOT ADDRESSED IN SUPPLEMNTAL MATERIAL REVIEWED

Engine Models

The engine model is the most important element in successfully modeling the capability of future vehicles, since it is the responsible for the largest loss of energy. It is also one of the most difficult aspect to predict since it involves many complicated processes (*i.e.* combustion, compressible flow) which must be considered in parallel with emissions compliance (*i.e.* in-cylinder formation, catalytic reduction.) Because of this, this sub-model must be viewed with extreme scrutiny in order to ensure quality outputs from the model.

The engine models are "defined by their torque curve, fueling map, and other input parameters." This implies that the maps are static representations of fuel consumption versus torque, engine speed, and other unknown input parameters. Generally speaking, representing engine performance in this fashion is consistent with typical practice for this class of modeling.

This comment deals only with the representation of the engine performance in simulation, the generation of the data contained within the map is much more challenging.

The report outlines two methods were used to produce engine models. The first method was used for boosted engines and relied upon published data on advanced concept engines which would represent production engines in the 2020-2025 timeframe. The second method was used with Atkinson and diesel engines and somehow extrapolated from current production engines to the 2020-2025 time frame. The description of both of these methods in the report is unsatisfactory. It also fails to address how the various technologies are used to build up to a single engine map for a specific powertrain. Validation, to the extent possible with future technologies, is also lacking in this area.

This reviewer took some time to look at the data via the tool provided. One table is shown in Figure 1 which shows some unexpected results. The results are for a small car with the dry clutch transmission and it shows the baseline engine having superior fuel economy over all other non-hybrid powertrain options. This is unexpected behavior and, since there is minimal transparency in the model, it cannot be investigated any further.

Engines	FTP	HWFET	US06
Baseline	42.1	62.5	37.0
Stoich_DI_Turbo	46.3	55.3	33.7
Lean_DI_Turbo	48.3	56.4	33.9
EGR_DI_Turbo	48.2	57.6	35.2
Atkinson_CPS	44.5	59.0	35.4
Atkinson_DVA	45.5	57.1	34.5

Figure 1: Simulation Results Different Engines for Small Car with 8Dry_DCT and all other Parameters Constant

<u>Suggested Corrective Action:</u>

1. Provide fuel and efficiency map data for all engines used in simulation
2. Describe what the “other inputs” are to the engine maps
3. Provide specific references of which published data was used to predict performance of the future engines. Some references are given, however, it is not clear how exactly these references are used.
4. Wherever possible, provide validation against data on similar technologies
5. Describe in detail the approach used to “stack up” technologies for a given powertrain recipe

Aftertreatment/Emissions Solutions

Based on the report, it seems that emissions solutions are assumed to be available for all powertrain technology packages selected. The report discusses this in some qualitative detail in section 4.2.2 with respect to lean-stoichiometric switching. This discussion is somewhat incomplete, in that the way it is written it assumes operating at stoichiometry lowers exhaust gas temperature. In reality, switching from lean to stoichiometric operation at constant load results in higher exhaust gas temperatures. Despite this factual inconsistency, it is indeed generally better to operate a temperature sensitive catalyst hot and stoichiometric or rich rather than hot and lean – so the concept of lean-stoich switching is valid even if the explanation provided is not. Even without this factual inconsistency, some additional discussion of aftertreatment systems would be of benefit given that lean-burn gasoline engines are at present a well-known technology for many years that is still problematic with respect to emissions control. A separate issue is the topic of fuel enrichment for exhaust temperature management which will have an important impact on emissions and, if emissions are excessive, reduce the peak torque available from an engine.

Suggested Corrective Action:

1. Provide better evidence that powertrain packages have credible paths to meet emissions standards
2. Provide evidence that fuel enrichment strategies are consistent with emissions regulations

Advanced Valvetrains

Two types of advanced valvetrains were included in the study, cam-profile switching and digital valve actuation. Both of these technologies are aimed at reducing pumping losses at part-load. The impact of these technologies is difficult to predict using simplified modeling techniques and typically require consideration of compressible flow and a 1-D analysis at a minimum. Even with an appropriate fidelity model, these systems require significant amounts of optimization in order to determine the best possible performance across the torque-speed plane of the engine. It is unclear how these systems were used to generate accurate engine maps given the level of detail provided in the report.

Suggested Corrective Action:

1. Describe how variable valve timing technologies were applied to the base engine maps
2. Describe the process of determining the extent of the efficiency improvement
3. Describe how optimal valve timing was determined across the variety of engines simulated

Direct Injection Fuel Systems

Because of the availability of research and production data in this area, it is expected that performance from this technology was used to predict performance rather than any type of modeling approach. That being said, the report does not describe where or how this data might have been used to develop the fuel consumption map of the engines simulated nor what data sources were used.

Suggested Corrective Action:

1. Cite sources of data used to predict DI performance
2. Describe how this data was used to develop the future engine performance maps
3. Provide validation of modeling techniques used

Boosting Systems

Boosting was applied to many of the different powertrain packages simulated. Beyond stating what maximum BMEP that was achievable, very little is mentioned in how the efficiency of the boosted engines were determined. Among other factors, boosting often creates a need for spark retard which costs efficiency if compression ratio is fixed. These complex issues are tied to combustion which is inherently difficulty to model. This aspect of the engine model is not well documented in the report.

Suggested Corrective Action:

1. Describe the process of arriving at the boosted engine maps
2. Describe how factors like knock are addressed in the creation of these maps

Engine Downsizing

Engine scaling is used extensively in the report. Basic scaling based on brake mean effective pressure is common in modeling at this level of fidelity, thus, this does not need any special description. However, the report mentions some means of modeling the increased relative heat loss with small displacement engines which is not a standard technique. The model or process used to account for this effect should be explicitly described given that engine size is one of the key parameters in the design space.

Suggested Corrective Action:

1. Properly document the process of scaling engines
2. Validate the process used to scale engines

Warm-Up Methodology

The report describes a 20% factor applied to bag 1 of the FTP-75 for baseline vehicles and a 10% factor applied to the advanced vehicles. The motivation for these factors is described qualitatively and is valid, as many organizations are currently investigating strategies to selectively heat powertrain components to combat friction effects. However, the values for these factors that were selected are not backed up with any data or citation. It is suspicious that the two values cited are such round numbers - the data from which these numbers are derived should be cited. Because of the complexity of this phenomenon, some type of empirical model is justified. The model described in the report is not sufficiently validated to judge its suitability.

Suggested Corrective Action:

1. Cite sources of data for 10% and 20% factors applied to the cold bag fuel economy data
2. Cite and/or validate the modeling approach used

Accessory Models

The accessory model is divided into electrical and mechanical loads. The electrical sub-model assumes alternator efficiency's of 55% and 70% for the baseline and advanced vehicles respectively. Given the required simplicity of the model, a simple model like this is likely acceptable, however, there is no source described for the alternator efficiencies. The base electrical load of the vehicle is mentioned briefly, however, no numerical values are given for each vehicle class or any type of model described.

The electrical system also includes an advanced alternator control which allows for increased alternator usage during decelerations for kinetic energy recovery. The control description given is valid but simplistic, but seems to fit the expected level of accuracy required for the purpose. There is an issue regarding with the approach for modeling the battery during this process. When charging the battery at the stated level of 200 amps, the charging efficiency of the battery will be relatively poor. During removal of the energy later, there will once again be an efficiency penalty. There is no description of a low-voltage battery model in the report nor any explicit reference to such charge/discharge efficiencies. Additionally, an arbitrary limit of a 200 amp alternator is defined for all vehicle classes – it is unlikely that a future small car and a future light heavy duty truck will have an alternator with the same rating.

On the mechanical side, it is assumed that "required accessories" (*e.g.* engine water pump, engine oil pump) are included in the engine maps. The mechanical loading of a mechanical fan is mentioned but no description of the model which, at a minimum, should be adjusted based on engine speed and engine power.

Suggested Corrective Action:

1. Cite and/or validate the alternator efficiency values of 55% and 70%
2. Account for charge/discharge losses in the advanced alternator control and/or describe the 12V battery model used for the simulation
3. Describe, cite, and validate the accessory fan model used in the simulation
4. Justify the use of a 200 Amp advanced alternator across all of the vehicle platforms.

Engine Technology "Stack-Up"

There are a host of different technologies superimposed to create the future powertrain technologies. There is not a clear process described on how this technology "stack-up" is achieved. For instance, an advanced engine technology may allow for greatly improved BMEP. Greatly improved BMEP often comes at the expense of knock limits which are difficult to model even with sophisticated modeling techniques. In this simulation, many layers of powertrain technology are being compounded upon each other which will not simply sum up to the best benefits of all of the technologies – there are simply too many interactions. At the level of modeling described, which are maps which are altered in various unspecified ways; it is not clear how the technology stack-up is captured.

Suggested Corrective Action:

1. Describe in greater detail the approach used to model technology stack-up on the advanced vehicles
2. Provide some form of validation that this approach is justified

Baseline Hybrid Models

The following subsections deal with issues related to the hybrid component models.

Hybrid Control Strategy

Hybrid vehicles are particularly challenging to model because of the extra components which allow multiple torque sources, and thus, require some form of torque management strategy (*i.e.* a supervisory control.) The report briefly describes a proprietary supervisory control strategy that is used to optimize the control strategy for the FTP, HWFET, and US06 drive cycle. The strategy claims to provide the "lowest possible fuel consumption" which seems to be somewhat of an exaggeration – this implies optimality which is quite a burden to achieve and verify for such a complicated problem. The strategy also is reported to be "SOC neutral over a drive cycle" which is also difficult to achieve in practice in a forward looking model. Once can get SOC with a certain window, however, short of knowing the future or simply not using the battery - it is impossible to develop a totally SOC neutral control strategy.

Another factor that must be considered is that a hybrid strategy that achieves maximum fuel efficiency on FTP, HWFET, and US06 does not consider many other relevant factors. Performance metrics like 0-60 time and drivability metrics often suffer in practice. In today's hybrids, the number of stop-start events is sometimes limited from the optimum number for efficiency because of the emissions concerns. Because of these factors and others, a strategy achieving optimal efficiency may be higher than what can be achieved in practice.

Without even basic details on the hybrid control strategy, it is simply not possible to evaluate this aspect of the work. Because of the batch simulations with varying component sizes and characteristics, this problem is not trivial. Supervisory control strategies used in practice and in the literature require intimate knowledge of the efficiency characteristics and performance characteristics of all of the components (engine, electric motors/inverters, hydraulic braking system, and energy storage system) to develop control algorithms. This concern is amplified by the lack of validation of the hybrid vehicle model against a known production vehicle. It is unclear how a "one-size fits all" control strategy can be truly be perform near optimal over such widely varying vehicle platforms.

A last comment is that there is no validation of the HEV model against current production vehicles. At a minimum, the Toyota Prius has been dissected sufficiently in the public domain to conduct a validation of this class of hybrid electric vehicle.

Suggested Corrective Action:

1. Better describe the hybrid control strategy and validate against a current production baseline vehicle
2. Validate that the HEV control algorithm performs equally well on all vehicle classes
3. Validate that other vehicle performance metrics, like emissions and acceleration, are not adversely impacted by an algorithm that focuses solely on fuel economy. The emission side of things will challenge to validate with this level of model, however, some kind of assurance should be made to these factors which are currently not addressed at all.

Electric Traction Components

The model of electric traction components is not discussed in any detail, as the only mention in the report is that current technology systems were altered by "decreasing losses in the electric machine and power electronics." Given the importance of the electric motor and inverter system in hybrids this is not acceptable.

Suggested Corrective Action:

1. Describe the method used to model electric traction components
2. Provide validation/basis for the process used to generate future technology versions of these components
3. Describe the technique used to scale these components

HEV Battery Model

Battery models for HEVs are necessary to adequately model the performance of an HEV. The report provides no substantive description of the battery pack model, other than that the model was developed by "lowering internal resistance in the battery pack to represent 2010 chemistries under development." Battery pack size is also not a currently a factor in the model – this has a impact of charge and discharge efficiency of the battery pack.

Suggested Corrective Action:

1. Describe the method used to model the HEV battery

2. Provide validation/basis for the process used to generate future technology versions of the battery
3. Describe the technique used to scale the HEV battery

Transmissions

This peer reviewer is not as well-practiced in transmissions as in other areas in this review. Because of this, a more limited review was conducted of this aspect of the report. As with the other areas of the report, the general concern in this area is the inadequacy of documentation of the modeling approach and validation. Generically, the same issues noted above are applicable here:

1. Cite data sources used in modeling
2. Validate models wherever possible
3. Fully describe transmission models/maps and processes used to generate them
4. Fully describe clutch/torque converter models/maps and processes used to generate them
5. Fully describe the process used to generate shift maps and the operation of the shift controller
6. Fully describe the lockup controller (*i.e.* how soon can it enter lockup after shifting?)
7. Fully describe the process for modeling torque holes during shifting
8. Fully describe the model used for the final drive (*i.e.* inputs/structure/outputs)

Data Analysis Tool

The vehicle simulator is used to generate several thousand simulations using a DOE technique. This data is then fit with a neural-network-based response surface model in which the "goal was to achieve low residuals while not over-fitting the data." This response surface model then becomes the method from which vehicle design performance is estimated in the data analysis tool. In this case, the response surface model is nothing more than a multi-dimensional black-box curve fit. There was no error analysis given in the report regarding this crucial step. By way of example, the vehicle simulator could provide near perfect predictions of future vehicle performance; however, a bad response surface fit could corrupt all of the results.

Suggested Corrective Action:

1. Provide error metrics for the neural network RSMs (*i.e.* R^2, min absolute error, max absolute error, error histograms, error standard deviation, *etc*.) before combining the fit and validation data sets
2. Provide the error metrics described above for the RSMs after combining the fit and validation data sets
3. Provide validation that the data analysis tool correctly uses the RSM to predict results very close to the source data (*i.e.* demonstrate the GUI software behaves as expected)

Conclusions

As outlined in the executive summary, it was not possible to answer the charge questions provided for this peer review due to lack of completeness in the report. Thus, this report was aimed at providing feedback on what information would be helpful to allow a reviewer to truly evaluate the spirit of the charge questions. With the above in mind, the following conclusions are made.

The modeling approach describe in the report *could* be appropriate for the simulation task required and is generally consistent with approaches used by other groups in this field. The conclusions from the report *could* very well be sound; however, there is insufficient information and validation provided in the report to determine if this is the case. The technique used to analyze the mass simulation runs *could* also be sound, although the accuracy of the response surface model is not cited in the report.

These issues are summarized in the following key areas:

1. The process of arriving at the performance of the future technologies is not well described
2. The majority of models are only described qualitatively making it hard or impossible to judge the soundness of the model
3. Some of the qualitative descriptions of the models indicate that models do not consider some important factors
4. Because of the qualitative nature of the model descriptions, there is a major lack of transparency in the inputs and parameters in the models

5. Where precise value(s) are given for parameters in the model, the report generally does not cite the source of the value(s) or provide validation of the particular value
6. Validation of the model and sub-models is not satisfactory (It is acknowledged that many of these technologies do not exist, but the parameters and structure of the model have to be based on something.)

Supplemental Review

After the main review, some supplemental information was provided for further review. Comments on this material are found below and are organized by the title of the file reviewed.

General Comments

The supplemental review material provided some answers to questions posed above, but in general, did not provide the level of detail necessary to ensure a thorough review of the process. *The conclusion of this reviewer remains similar as on the original review, which is that there were no serious flaws found in the work, however, there were enough omissions that it is not possible to accurately judge if the predictions made are accurate*. The biggest concern in this work is the lack of validation and/or citation of where data and models are coming from. There are numerous maps that are presented in the follow-up material, however, these maps had to have originated from some process (which needs documented) and should be compared against some kind of validation. Despite the lack of documentation provided, the work is generally that of a project team that is competent in this field of study.

Cold Start Correction Methodology

The correction used to adjust fuel economy for cold start is described in this presentation. The method is based on two pieces of information:

1. A set of three tests from a single vehicle's instantaneous fuel multiplication correction factor
2. A piece of EPA data which shows a fleet-wide average for 2007 of the instantaneous fuel multiplication correction factor

The instantaneous fuel multiplication correction factor is not described in the presentation, however, it is assumed to be the sum of the "short term fuel trim" and "long term fuel trim." If this is the case, then this value doesn't correlate to increased fuel consumption, but rather, to errors in the injector characterizations, fuel property assumptions, and air estimation algorithm in the engine controller. The engine controller is going to maintain stoichiometry based on oxygen sensor measurements, these trim values are the simply the feedback correction values required to do this based on the feedforward algorithm in the ECU. By way of example, I could alter the fuel tables of an ECU by 15% which would cause the feedback control system to correct by an opposite 15%. This would not change the fuel consumption of the vehicle once the control system has corrected it, which would happen in seconds.

I don't disagree necessarily with the magnitude of the outcomes, since they are based mostly on EPA bag fuel economy data. If I am correct in my understanding of the correction factor then the method is not valid.

Alternator Regen Shift Optimizer

Alternator Regen

The alternator regeneration strategy is not well documented. The key system specifications, such as max alternator output and efficiency, are listed as assumptions without a data source for validation. The efficiency of the battery is not mentioned in this nor other presentations that this reviewer has read – battery efficiency for a lead acid battery at high currents is poor, this would have an impact on the recovery of energy. Strategies like this are disruptive to drivability and this issue is not discussed in the presentation.

Shift Optimizer

Shifting strategy impacts efficiency, performance, and drivability. Manufacturers are aware of this and balance all three when calibrating shift maps. Changing baseline shift maps to improve efficiency will have an impact on the other metrics which are also important to the vehicle. Additionally, it is not clear how the optimized shift strategy was developed, what the shift strategy is, or how it will be applied to the range of transmissions in the study. It is stated that is optimizes BSFC, however, there are other constraints that must be applied in addition to this.

Battery Warm up 1, Battery Warm up 2

The battery model described has the following possible problems:

1. The model is relatively simple – but could potentially work for the application and generally is consistent with the fidelity of the rest of the model.
2. The model references ambient temperature for heat rejection. Most HEVs pull in cabin air rather than outside air for cooling, thus, this will cause modeling error.

3. Adjusting the M_{bat} x Cp_{bat} term by 200% is a red flag that something might be fundamentally wrong with either the model formulation or the data used in the model. There should be minimal errors in the mass estimation of the pack and the specific heats of battery modules can be found in the literature or through testing.
4. The method of handling battery packs of different classes of vehicles is not described, nor are the actual parameters for these different models disclosed.

Turbo Lag

The data and methods used in modeling turbo lag are appropriate and there is sufficient explanation and data to support the model.

Future Friction Assessment

The provided presentation does not describe how engine friction projections to 2020 are made or how they are modeled. It provides some data from 1995 to 2005, however, it does not provide any useful insight into how this information is used.

Scaling Methodology Review

With one exception, the scaling methodology appears to be sound given the information provided in the presentation. The curve used to adjust BSFC with displacement ratio is not supported with data or any citation of where it originated. The motivation for this correction seems valid, however, it needs to be supported with data.

SI Engine Maps and Diesel Engine Maps

The baseline engine map data is shown in a series of figures and references are provided for the specific vehicle that the map is for. It is assumed that this indicates that this data has been measured experimentally. If this is the case, then this is well documented.

For the 2020 engine maps, there is insufficient detail in this presentation on how the maps were generated. Getting accurate simulation requires careful validation of the model as well as the data in the model – these engine maps are not sufficiently well documented for me to make a judgment on their suitability for the overall goal of the simulator. I am well aware that these future engines do not exist, but there had to be some process of generating these engine maps. Without more information on this process it is simply not possible to comment on their accuracy.

BSFC Map Comparisons

I reviewed this but do not have any substantive comments. All of the figures compare pseudo-virtual engines with other pseudo-virtual engines. A comparison back to a known, experimentally validated engine current engine would have been more useful for me as it would allow one to see the magnitude of improvements that were assumed for the 2020 engines and where on the map these improvements were made.

Input Data Review

The documentation on the Diesel engine maps was helpful; however, it did not discuss how the 2020 engine maps were developed. This is critical for having confidence in the predictions made for the Diesel powertrains in 2020.

The shift strategy is discussed qualitatively; however, it is not described in enough detail to understand exactly how it is accomplished. Shift schedules are shown, however, no validation is shown that would indicate that these shift schedules are optimal as claimed.

The torque converter models are standard models, thus, the provided documentation is adequate.

Hybrid Controls Presentations

Several hybrid controls presentations were provided, however, it was difficult to piece together what information superseded the other since they were provided out of context. There were several good slides showing dynamic programming results of different control scenarios, however, it is assumed that this was not used for the mass simulation since it would be computationally impractical. Thus, I expected to see some results comparing the offline control results to the actual control used in the vehicle simulation, however, this was not found. The major concern in this area is developing a control strategy that is near optimal for a wide variety of hybrid architectures as well as architectures with varying component types and sizes. Without further validation in this area it is not clear that the hybrid results are valid since the control has such an important role in this.

Review of supplemental materials

to the report

COMPUTER SIMULATION OF LIGHT-DUTY VEHICLE TECHNOLOGIES FOR GREENHOUSE GAS EMISSION REDUCTION IN THE 2020-2025 TIMEFRAME

18 August 2011

Prepared for

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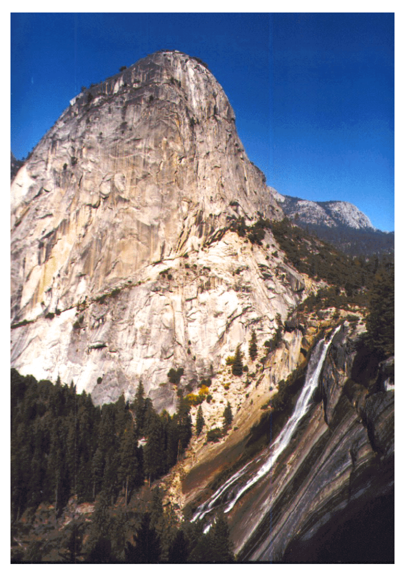

OVERVIEW

Reviewers of the report, *Computer simulation of light-duty vehicle technologies for greenhouse gas emission reduction in the 2020-2025 timeframe,* 6 April 2011, prepared by Ricardo, Inc. requested documentation of data used in the computer simulation. Of particular interest were the engine maps and other performance information incorporated in the model. Ricardo provided 44 documents that included proprietary engine maps, proprietary Ricardo reports, technical papers from the open literature, responses to USEPA questions, and other materials.

REVIEW

For each document, its title, a brief description of the nature of the material contained, and comments on the nature of the material follows:

1) Ricardo, *Action Item Response*, 16 Feb 10, 15 p. (proprietary)

A response to an EPA inquiry, this document deals with engine maps, engine map comparisons, engine map plots, transmissions, batteries, motor and generator efficiency maps.

Comment: Ricardo responses and data selection seem reasonable.

2) Ricardo, *Baseline Camry with Alternator Regen and Shift Optimizer Development of Optimized Shifting Strategy Light Duty Vehicle Complex Systems Simulation EPA Contract No. EP-W-07-064, work assignment 2-2,* 15 Apr 10, 10 p. (proprietary)

This document provides data on effectiveness of shift optimizer, including alternator regen, over the FTP and HWFET.

Comment: Seems reasonable, improvements are greater on FTP than HWFET.

3) Carlson, R., et al., Argonne National Laboratory, *On-Road Evaluation of Advanced Hybrid Electric Vehicles over a Wide Range of Ambient Temperatures EVS23 – Paper #275*, 15 p.

Paper reports on-road and dynamometer testing of two hybrid vehicles at cold (-14 degC) and hot (33 decC) conditions. Fuel economy increases with temperature (except for highest temperatures with the system which does not limit battery temperature).

Comment: Paper provides data showing importance of temperature on hybrid vehicle fuel economy. These data are used by Ricardo to validate their battery warm up model, see next document.

4) Ricardo, *Hybrid Battery Warm Up Model Validation – Update, Light Duty Vehicle Complex Systems Simulation* ,EPA Contract No. EP-W-07-064, work assignment 2-2, 15 Mar 10, 5 p. (proprietary)

This report presents a simple battery heat transfer model for battery warm up and compares with Argonne National Laboratory of the previous document.

Comment: Model produces adequate prediction of battery temperature.

5) Ricardo, *BSFC Map Commparisons, LBDI vs EGR Boost & DVA for STDI, OBDI, & EGR Boost, Light Duty Vehicle Complex Systems Simulation*, EPA Contract No. EP-W=07=064, work assignment 2-2, 24 Feb 10, 20 p. (proprietary)

Comparison of engine technologies in terms of maps of percent difference in bsfc in bmep vs rpm space allows visualization

Comment: Straight forward data analysis, presumably as requested by USEPA. Should aid in understanding technology performance differences.

6) Mischker, K. and Denger, D., *Requirements of a Fully Variable Valvetrain and implementation using the Electro-Hydraulic Valve Control System EHVS,* 24th International Vienna Engine Symposium 2003, 17 p.

This paper describes an electro-hydraulic valve system (EVHS) and limited data on reduction in bsfc.

Comment: This would seem to be of limited quantitative value since technology is well advanced beyond 2003.

7) Ricardo, *Engine and Battery Warm-Up Methodology, Light Duty Vehicle Complex Systems Simularion,* 17 Feb 10, 16 p. (proprietary)

Document reviews engine and battery warm-up strategies and provides a simple model.

Comment: The approach to battery warm-up is uncertain. Points to importance of test cycle (FTP for fuel economy compliance versus test for EPA label versus real-world).

8) Ricardo, *Response to EPA Questions on the Diesel Engine Fuel Maps, Supplemental Graphs for Word Document,* 16 Feb 10, 11 p. (proprietary)

Document presents proposed diesel engine maps for MY2020+ vehicles.

Comment: Anticipated technologies are listed but how the maps were generated is not described. Maps seem reasonable.

9) Ricardo, *Assessment of Technology Options, Technologies related to Diesel Engines,* 23 Nov 09, 17 p.

Overview predicts continuation of low uptake in the U.S. LDA and LDT markets. Review deals with various engine technologies to improve efficiency. Individual improvements <1-5%. Most promising is electric turbo-compounding (bottoming cycle to recover exhaust thermal energy to produce electricity).

Comment: Individual technology assessments seem reasonable. There is no analysis of integrating several technologies.

10) Ricardo, *EBDI Project Overview, Ethanol Boosted Direct Injection,* Nov 09, 8 p.

This study examines ethanol boosted direct injection (EBDI) to optimize engine operation of E85 fuel. Possibility exists to match or exceed diesel performance and reduce CO_2 emissions.

Comment: It is not clear if comparison of EBDI and diesel is a equal technology level.

11) Ricardo, *Hybrid Controls Follow-up*, 10 Sep 11, 3 p. (proprietary)

Report discussed motor/general efficiency map used for 2020 technology. Projected efficiencies peak at 95% but most P2 hybrid application if below 90% efficiency.

Comment: I am not qualified to assess if the projected motor/generator efficiencies are appropriate for 2020-2025 as reported, but they seem low for 15 years in the future.

12) UOM, *HiTor® for elecgtric, hybrid electric, and fuel cell powered vehicles*, 18 Aug 09, based on test data map, 5 p.

Describes power electronics for motor generator control, including an efficiency map for combined controller and motor based on test data.

Comment: Efficiency maps seem reasonable.

13) Odvarka, E., et al., *Electgric motor-generator for a hybrid electric vehicle, Engineering Mechanics, 16, 131-139,* 2009, 9 p.

Describes electrical machine options of hybrid electric vehicles. Includes efficiency maps for four technologies.

Comment: Data are of general interest, but date from 2003.

14) UOM, *PowerPhase®75 for electric, hybrid electric, and fuel cell powered vehicles,* not dated, 6 p.

Described power electronics of vehicle electric power.

Comment: Similar to earlier brochure on power electronics, including efficiency map.

15) Ricardo, *Future Engine Friction Assessment—Response to Action Item Question SI Engine #4,* 18 Feb 11, 4 p. (proprietary)

Projects continued reduction in engine friction, 2010-2020.

Comment: Data provide confirm projection.

16) Ricardo, *Revised Follow-up Answers to 8 April 2010 Meeting with EPA and Ricardo,* 19 Apr 10, 8 p. (proprietary)

Presents fueling maps for several technologies.

Comment: Adds to documentation of engine map data.

17) Alger, T., Southwest Research Institute, *Examples of HEDGE Engines,* 2009, 4 p.

Presents engine map for a 2.4 L I4 High-Efficiency Dilute Gasoline Engine (HEDGE) engine and compares with TC GDI engine, diesel engine.

Comment: Adds to documentation of engine map data.

18) Ricardo, *Hybrid Controls Peer Review*, 18 Feb 10, 31 p. (proprietary)

Review of hybrid control technologies for various architectures. Review of battery operation in cold weather.

Comment: Thorough description of technologies and their operation characteristics. Battery discussion covers similar material to an earlier paper.

19) Ricardo, *Hybrids Control Strategy,* 6 Aug 10, 41 p. (proprietary)

Discusses development of control strategies for P2 and Power Split hybrids.

Comment: includes efficiency maps and substantial technical detail including vehicle mass effect.

20) Ricardo, *Simulation Input Data Review,* 4 Feb 10, 14 p. (proprietary)

Described hybrid architectures with emphasis on machine-inverter combine efficiencies, including efficiency maps.

Comment: More data, seems reasonable.

21) Ricardo, *Assessment of Technology Options,* 18 Nov 09, 14 p. (proprietary)

Assessment of hybrid technologies using evaluation template.

Comment: Treats a range of hybrid technologies, including series hydraulic, giving projections of CO_2 reduction benefits.

22) Ricardo, *Simulation Input Data Review,* 2 Feb 10, 30 p. (proprietary)

Document review modeling parameters for vehicle performance simulations, including engine efficiency maps for a range of engine and transmission technologies.

Comment: This is the kind of data that we requested. Includes shift strategies. Seems reasonable and well-documented.

23) Trapp, C., et al., *Lean boost and NO_x—strategies to control nitrogen oxide emissions,* (no date), 23 p.

Technical paper that describes lean burn direct injection (LBDI) engines, SCR NO_x control, and more. Includes some emission control cost data.

Comment: Not clear how this related to Ricardo's model development for EPA.

24) Trapp, C., et al., ***NOx emission control options for the Lean Boos downsized gasoline engine,*** **(2 Feb 07), 34 p.**

Paper compares lean NO_x trap and selective catalytic reduction technologies. Includes some engine map data for NO_x emissions. Includes cost data for aftertreatment.

Comment: Good academic paper with useful data. Not clear what or how Ricardo used.

25) Trap, C., et al., ***NO_x emission control options for the lean boost downsized gasoline engine,*** **(2 Feb 07), 27 p.**

Paper review international emissions regulation and technologies to meet.

Comment: This paper contains some of the same information as the preceding two. Simulated date presented, again for SCR and LNT technologies.

26) Ricardo, ***Lean/Stoichiometric switching load for 2020 Hybrid Boost Concept,*** **(no date), 2 p.**

Presents space velocity and fuel maps.

Comment: Relevance not clear.

27) Ricardo, ***Proposed Lean/Stoichiometric switching load for hybrid boost concept,*** **29 Apr 10, 1 p.**

Identifies proposed lean zone operating region on engine map.

Comment: relevance not clear.

28) Lymburner, J.A., et al., ***Fuel consumption and NO_x Trade-offs on a Port-Fuel-Injected SI Gasoline Engine Equipped with a Lean NO_x Trap,*** **4 Aug 09, 20 p.**

This technical paper examines the trade-off between NO_x control and CO_2 emissions.

Comment: Good work but relevance not clear.

29) Lotus(?), (from Kapus, P.E. et al., May 2007), ***Comparison to other downsized engines***

This one figure is a partial engine map with context vague.

Comment: Significance is not clear.

30) Turner, J.W.G., et al., *Sabre: a cost-effective engine technology combination of high efficiency, high performance and low CO_2 emissions, Low Carbon Vehicles, May 09, IMechE Proceedings,* 14 p.

This paper describes a technology for reducing CO_s emissions in a downsized engine. The Sabre engine is a collaboration between Lotus Engineering and Continental Automotive Systems.

Comment: Limited performance data provided.

31) Ricardo, *Conventional Automatic Nominal Results,* 16 Mar 10, 17 p. (proprietary)

This presentation includes mileage versus 0-60 mph time maps for a range of vehicles (light duty to large truck). Also presented are comparisons of fuel economy for different regulatory test cycles and technologies.

Comment: Significance not clear.

32) Ricardo, *Report on light-duty vehicle technology package optimization,* 4 Dec 09, 32 p.

This is a progress report on Ricardo's modeling work for the EPA. A range of engine technologies, hybrid technologies, transmission, and vehicle technologies are described.

Comment: A comprehensive list of near term technologies are included. The report is incomplete and optimization apparent is not included here.

33) Ricardo, *Revised follow-up answers for hybrid action items,* 23 Jun 10, 16 p. (proprietary)

This report answers questions on electric drive train efficiency, battery characteristics, and available braking energy, and more.

Comment: Interesting data, but implication not clear.

34) Ricardo, *Response to questions regarding the generation of the diesel fuel maps for fuel efficiency simulation,* 16 Feb 10, 10 p. (proprietary)

Paper answers a series of EPA questions on how the diesel fuel maps were generated.

Comment: This is relevant information and provides a convincing description of the technical basis for the diesel fuel maps.

35) Ricardo, *Scaling Methodology Review,* 19 Jan 10, 9 p.

This document explains the scaling methodology used in the EASY5 vehicle model.

Comment: This description in clear and useful.

36) Ricardo, *SCR as an Enabler for Low CO_2 Gasoline Applications,* no date, 35 p.

This presentation describes technology and implementation for exhaust NO_x reduction for lean burn gasoline engines.

Comment: Comprehensive discussion of technology, but if and how inconcorporated in the model not clear.

37) Ricardo, *Simulation Input Data Review,* 18 Mar 10, 17 p. (proprietary)

This document reviews the engine maps used in the model. Includes are examples of the baseline maps plus modifications associated with a range of technologies. Data apply to all 7 vehicle classes.

Comment: This is the documentation that was missing in the earlier review material. Looks reasonable and is reassuring.

38) Ricardo, *Assessment of Technology Options*, 19 Nov 09, 22 p. (confidential)

This document reviews and rates a range of spark-ignition adaptable technologies to reduce CO_2 emissions. Biofuels are included.

Comment: An interesting compendium but some previously reported.

39) Shimizu, R., et al., *Analysis of a Lean Burn Combustion Concept for Hybrid Vehicles,* 2009, 13 p.

A technical paper, this document describes early (1984) and more recent Toyota lean burn engines.

Comment: Interesting technical description but no clear if or how used in the Ricardo model.

40) Takoaka, T., et al., Toyota, *Super high efficient gasoline engine for Toyota hybrid system*, (no date), 16 p.

This paper describes the hybrid system, IC engine interaction that allows increased IC engine efficiency.

Comment: Of general interest but application to the model not clear.

41) Ricardo, *Assessment of Technology Options*, *Technologies related to Transmission and Driveline*, 19 Nov 09, 21 p.

This document described transmission technologies, including timing of their introduction.

Comment: Seems reasonable.

42) Ricardo, *Transient Performance of Advanced Turbocharged Engines,* 15 Sep 10, 19 p. (proprietary)

This report reviews expected advances in boosting technologies and anticipated effects on vehicle performance.

Comment: Interesting information but how it impacts model is not clear.

43) Kapus, P., *Potential of VVA Systems for Improvement of CO_2 Pollutant Emission and Performance of Combustion Engines,* 30 Nov 2006, 9 p.

This is a technical paper describing variable valve actuation approaches and performance effects.

Comment: Useful general technical information.

44) Ricardo, *Assessment of Technology Options, Technologies related to Vehicle-level Systems,* 24 Nov 09, 16 p.

This review of vehicle technologies that can improve vehicle efficiencies provides a basic description and information on expected levels of CO_2 reduction.

Comment: This is a clear description of anticipated improvements in vehicle technologies that reduce load and fuel consumption.

CONCLUSIONS

Ricardo has provided material, which is stated to be the data incorporated in the computer simulation. These data are consistent with the data expected to be the basis of the simulation. It is impossible to establish a precise correspondence between the data and the model. The performance data covered by the 44 separate documents seem reasonable and provide additional assurance that the simulation is soundly based on measured performance. There is no reason to doubt either the integrity or capability of Ricardo in their incorporation of appropriate data into their simulation model.

Appendix E. Draft Project Report by Ricardo

DRAFT PROJECT REPORT
COMPUTER SIMULATION OF LIGHT-DUTY VEHICLE TECHNOLOGIES FOR GREENHOUSE GAS EMISSION REDUCTION IN THE 2020–2025 TIMEFRAME

Prepared for:	Office of Transportation and Air Quality U.S. Environmental Protection Agency 2565 Plymouth Road Ann Arbor, Michigan 48105
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The following organizations contributed to this study:

Ricardo, Inc.
SRA International, Inc. (Perrin Quarles Associates, Inc.)
U.S. Environmental Protection Agency
California Air Resources Board
International Council on Clean Transportation

COMPUTER SIMULATION OF LIGHT-DUTY VEHICLE TECHNOLOGIES FOR GREENHOUSE GAS EMISSION REDUCTION IN THE 2020–2025 TIMEFRAME

EXECUTIVE SUMMARY

Ricardo, Inc. was subcontracted by SRA International, Inc. (SRA), under contract to the United States Environmental Protection Agency (EPA) to assess the effectiveness of future light duty vehicle (LDV) technologies on future vehicle performance and greenhouse gas (GHG) emissions in the 2020–2025 timeframe. GHG emissions are a globally important issue, and EPA's Office of Transportation and Air Quality (OTAQ) has been chartered with examining the GHG emissions reduction potential of LDVs, including passenger cars and light-duty trucks. This program was performed between October 2009 and March 2011.

The scope of this project was to execute an independent and objective analytical study of LDV technologies likely to be available within the 2020–2025 timeframe, and to develop a data visualization tool to allow users to evaluate the effectiveness of LDV technology packages for their potential to reduce GHG emissions and their effect on vehicle performance. This study assessed the effectiveness of a broad range of technologies, including powertrain architecture (conventional and hybrid), engine, transmission, and other vehicle attributes such as engine displacement, final drive ratio, vehicle weight, and rolling resistance on seven light-duty vehicle classes. The methodology used in this program surveyed the broad design space using robust physics-based modeling tools and generated a computationally efficient response surface to enable extremely fast surveying of the design space within a data visualization tool. During this effort, quality assurance checks were employed to ensure that the simulation results were a valid representation of the performance of the vehicle. Through the use of the data visualization tool, users can query the design space on a real time basis while capturing interactions between technologies that may not be identified from individual simulations.

This report documents the work done on the program “Computer Simulation of Light Duty Vehicle Technologies for Greenhouse Gas Emission Reduction in the 2020–2025 Timeframe.” This work has included identifying and selecting technologies for inclusion in the study, developing and validating baseline models, and developing the data visualization tool.

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1. INTRODUCTION

Ricardo was subcontracted by SRA International (SRA), under contract to the United States Environmental Protection Agency (EPA) to assess the effectiveness of future LDV technologies on future vehicle performance and GHG emissions in the 2020–2025 timeframe. GHG emissions are a globally important issue, and EPA's Office of Transportation and Air Quality (OTAQ) has been charged with examining the GHG emissions reduction potential of LDVs, including passenger cars and light-duty trucks.

SRA is an interdisciplinary environmental consulting firm specializing in environmental program development and implementation support, with a major focus on air quality and GHG reduction initiatives. In addition to the SRA–Ricardo team working for EPA, other stakeholders for the program included the International Council on Clean Transportation (ICCT) and the California Air Resources Board (ARB). Representatives from each stakeholder, together with EPA staff, formed the Advisory Committee for this project

Ricardo, Inc. is the U.S. division of Ricardo plc., a global engineering consultancy with nearly 100 years of specialized engineering expertise and technical experience in internal combustion engines, transmissions, and automotive vehicle development. This program was performed between October 2009 and March 2011.

The scope of the program was to execute an independent and objective analytical study of LDV technologies likely to be available in the 2020–2025 timeframe, and to develop a data visualization tool to allow users to evaluate the effectiveness of LDV technology packages for their potential to reduce GHG emissions. An assessment of the effect of these technologies on LDV cost was beyond the scope of this study.

This work was done in collaboration with EPA and its external partners, and the approach included the following activities:

- Extrapolate selected technologies to their expected performance and efficiency levels in the 2020–2025 timeframe.
- Conduct detailed simulation of the technologies over a large design space, including a range of vehicle classes, powertrain architectures, engine designs, and transmission designs, as well as parameters describing these configurations, such as engine displacement, final drive ratio, and vehicle rolling resistance.
- Interpolate the results over the design space using a functional representation of the responses to the varied model input factors.
- Develop a Data Visualization Tool to facilitate interrogation of the simulation results over the design space.

2. OBJECTIVES

The goal of this technical program has been to evaluate objectively the effectiveness and performance of a large LDV design space with powertrain technologies likely to be available in the 2020–2025 timeframe, and thereby assess the potential for GHG emissions reduction in these future vehicles while also understanding the effects of these technologies on vehicle performance.

3. BACKGROUND

3.1 Study Background

EPA and other program stakeholders have a mutual interest in improving the environmental performance and efficiency of cars, trucks, buses, and transportation systems to protect and improve public health, the environment, and quality of life. Additionally, reduction of GHG emissions—emphasizing carbon dioxide (CO_2)—is an increasing priority of national governments and other policymakers worldwide.

The purpose of this study is to define and evaluate potential technologies that may improve GHG emissions in LDVs in the 2020–2025 timeframe. These technologies represent a mixture of future mainstream technologies and some emerging technologies for the study timeframe.

3.2 Ground Rules for Study

Several ground rules for the study were agreed at the beginning of the program to bound the design space considered in the study. These ground rules identified content that should be included in the study as well as content that should be excluded.

Some examples of the ground rules include the following items for the technology assessment:

- Seven vehicle classes will be included, as described below
- LDV technologies must have the potential to be commercially deployed in 2020–2025
- Vehicle sizes, particularly footprint and interior space, for each class will be largely unchanged from 2010 to 2020–2025
- Hybrid vehicles will use an advanced hybrid control strategy, focusing on battery state of charge (SOC) management, but not at the expense of drivability
- Vehicles will use fuels that are equivalent to either 87 octane pump gasoline or 40 cetane pump diesel
- 2020–2025 vehicles will meet future California LEV III requirements for criteria pollutants, which are assumed to be equivalent to current SULEV II (or EPA Tier 2 Bin 2) levels

Likewise, the Advisory Committee agreed that the technology assessment for this program should exclude the following:

- Charge-depleting powertrains, such as plug-in hybrid electric vehicles (PHEV) or battery electric vehicles (EV)
- Fuel cell power plants for fuel cell-electric vehicles (FCEV)
- Non-reciprocating internal combustion engines (ICE) or external combustion engines
- Manual transmissions and automated manual transmissions (AMT) with a single clutch
- Kinetic energy recovery systems (KERS) other than battery systems
- Intelligent vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) optimization technology
- Bottoming cycles, such as organic Rankine cycles, for energy recovery
- Vehicle safety systems or structures will not be explicitly modeled for vehicles. A full safety analysis of the technologies presented in this report is beyond the scope of this study

The seven vehicle classes considered in this study are the following, with a currently available example vehicle given for each class:

1. Small (B-class) Car, such as the Toyota Yaris;
2. Standard (D-class) Car, such as the Toyota Camry;
3. Small Multi-Purpose Vehicle (MPV), such as the Saturn Vue;
4. Full Sized Car, such as the Chrysler 300;
5. Large MPV, such as the Dodge Grand Caravan;
6. Light-Duty Truck (LDT), such as the Ford F150; and
7. Light Heavy-Duty Truck (LHDT), such as the GM HD3500.

3.3 Technology Package Selection Process

The program team used the process shown in Figure 3.1 to identify the technology options described in Chapter 4 and downselect to the technology packages described in Chapter 5.

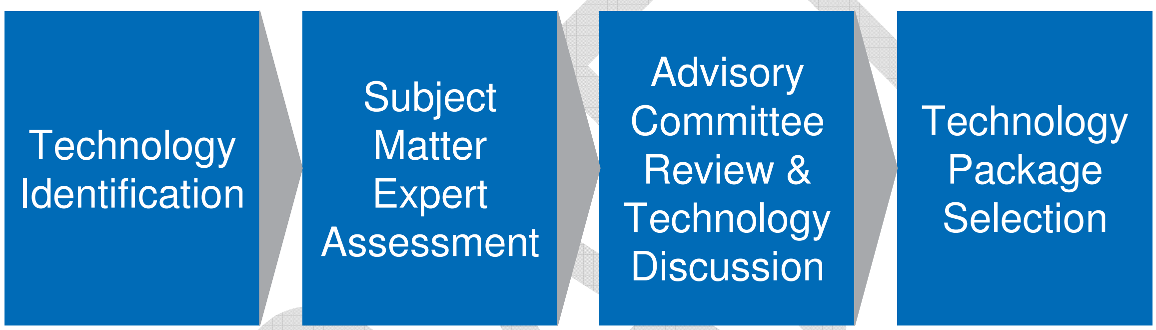

Figure 3.1: Technology package selection process.

The program team first developed a comprehensive list of potential technologies that could be in use on vehicles in the study timeframe, 2020–2025. These technologies were grouped by subject area, such as transmissions, engines, or vehicle, and given to Ricardo subject matter experts (SMEs) for assessment and evaluation. These SME assessments were reviewed with and discussed by the program's Advisory Committee. Technology options were assembled into technology packages for use in the vehicle performance simulations.

3.4 Complex Systems Modeling (CSM) Approach

Complex systems modeling (CSM) is an objective, scientific approach that supports decision making when there are a large number of factors to consider that influence the outcome, as with LDV development for vehicle performance and GHG emissions reduction. To be objective, performance metrics were identified by the Advisory Committee; these metrics were outputs of the vehicle performance simulation effort and characterize key vehicle attributes. To be scientific, the performance simulations use a physics-based modeling approach for detailed simulation of the vehicle.

The design of experiments (DoE) approach surveys the design space in a way that extracts the maximum information using a limited budget of simulation runs. The purpose of the DoE simulation matrix was to efficiently explore a comprehensive potential design space for LDVs in the 2020–2025 timeframe. The simulation matrix was designed to generate selected performance results over the selected drive cycles, such as fuel consumption or acceleration times.

A statistical analysis was used to correlate variations in the input factors to variations in the output factors. Because of the complex nature of the LDV configurations and constituent technology packages, a neural network approach was used to quantify the relationships between input and output factors over the design space explored in the simulations. The result of this analysis was a set of response surface models (RSM) that represent in simplified form the complex relationships between the input and output factors in the design space.

3.5 Data Visualization Tool

The Data Visualization Tool allows the user to query the RSM and develop an understanding of how various combinations of future technologies may affect GHG emissions and other vehicle performance metrics. Vehicle configurations with unacceptable performance, such as too-low combined fuel economy or too-slow acceleration times, can be excluded from further study.

The Data Visualization Tool uses the RSM set generated by the Complex Systems approach to represent the vehicle performance simulation results over the design space. These simulations cover multiple variations of vehicle configuration, including several combinations of advanced powertrain and vehicle technologies in the seven LDV classes.

The tool samples vehicle configurations from a selected subset of the design space by using Monte Carlo type capabilities to pick input parameter values from a uniform distribution. Defining selected portions of the design space and plotting the results visualizes the effect of these parameters on vehicle fuel economy and performance, allowing trade off analysis via constraints setting to be performed over a wide design space representing the 2020–2025 technologies as applied.

4. TECHNOLOGY REVIEW AND SELECTION

Following the process outlined above, a broad range of potential technologies were identified for consideration in the study. These technologies were evaluated qualitatively against the following criteria for further consideration:

- Potential of the technology to improve GHG emissions on a tank to wheels basis
- State of development and commercialization of the technology in the 2020–2025 timeframe
- Current (2010) maturity of the technology

Based on these criteria, a subset of the full list of technologies was selected for inclusion in the study. These technologies are described in this chapter.

In the study timeframe of 2020–2025, spark-ignited (SI) engines are projected to continue to be the dominant powertrain in the U.S. light-duty vehicle market, especially since the efficiency of SI engines is expected to approach the efficiency of compression ignition (CI, or diesel) engines at the required 2020–2025 emissions levels. Nevertheless, diesel engines are expected to contribute to future GHG emissions reduction, especially for the heavier vehicle classes. Thus, diesel engine technologies were also considered in the study.

The first two sections of this chapter therefore describe the technologies expected to appear in these future engines and specific engine configurations, respectively. The other sections in this chapter describe the transmission and driveline, vehicle, and hybrid system technologies that were included in the overall design space of the study. The implementation of these technologies in the vehicle performance models is described in Chapter 6, Vehicle Model.

4.1 Advanced Engine Technologies

The primary challenge for advanced engines in the 2020–2025 timeframe is to reduce GHG emissions and maintain performance without increasing criteria pollutants. This challenge is expected to be met through a range of improvements, from the application of highly-efficient downsized engines through to detailed optimization of components and systems. This section describes specific technologies or systems that are expected to be included in future engines, each of which supports the overall goal of reduced GHG emissions in future vehicles. The following section, 4.2, Engine Configurations, describes the complete engine technology packages that combine these technologies.

4.1.1 Advanced Valvetrains

Several advances in valvetrain technology are expected to be available in the study timeframe. These technologies are expected to apply to engines across the whole set of vehicle classes examined in the study.

Advanced valvetrain systems improve fuel consumption and GHG emissions mainly by improving engine breathing, thereby reducing pumping losses in the engine. The pumping loss mitigation provides larger benefits at part-load operation, such as during urban driving. Advanced valvetrains also support engine downsizing, which provides fuel consumption benefits across the complete engine operating map. Lastly, they can be used to support faster aftertreatment warm-up through varied timing, leading to additional, synergistic gains if the faster aftertreatment warm-up creates a benefit to tailpipe-out NO_x emissions that can be traded off to improve GHG emissions.

Two advanced valvetrain options, cam-profile switching and digital valve actuation, were included in the study and are discussed below.

4.1.1.1 Cam-Profile Switching Valvetrain

Cam-profile switching (CPS) systems use a hydraulically-actuated mechanical system to select between two or three cam profiles. CPS systems, such as the Honda VTEC, Mitsubishi MIVEC, Porsche VarioCam, and Audi Valvelift, have been developed by a number of Japanese and European manufacturers. CPS systems can be designed to improve low-speed torque or to improve fuel economy by reducing pumping losses at light load. CPS systems are applicable in all LDV classes. The benefit to GHG emissions is expected in part-load operation, and will therefore provide a larger benefit in city driving than in highway driving.

4.1.1.2 Digital Valve Actuation Valvetrain

Digital valve actuation (DVA) uses a mechanical, hydraulic, or electrical system to actuate the valves independently of a camshaft. The full realization of DVA in the study timeframe will be a camless DVA system, where there is no mechanical linkage between the engine crank and the valves. The engine fueling maps with DVA were assumed to use camless DVA systems, such as electrohydraulic or electromagnetic systems. Electropneumatic systems are less mature currently, but may yet be available late in the timeframe. An example DVA system in current production is the Fiat MultiAir system, an electro-hydraulic system (Fiat, 2009) that still uses a camshaft to provide the primary timing for the valve open and valve close events. The DVA system could be implemented to provide flexibility, with valve event timing, valve lift profiles, or both. As with the CPS systems, the main benefit in GHG emissions is a result of reducing pumping losses at part-load operation.

4.1.2 Direct Injection Fuel Systems

Direct injection (DI) fuel systems are the standard fuel injection system in use on current diesel engines. One of the significant changes expected by the 2020–2025 timeframe is a continued transition from port fuel injection (PFI) to DI in SI engines as well. For SI engines with DI, the fuel is injected directly into the combustion cylinder before being ignited. DI fuel systems inject the fuel at a higher pressure than PFI injectors do, and allow the use of multiple injection events to support advanced combustion control. SI engines with DI were first introduced in Japan in 1996, and an increasing number of new SI engines now feature DI.

DI improves fuel economy because it facilitates a higher compression ratio in the engine, which helps improve the engine's volumetric and thermal efficiency. Using DI improves fuel consumption across the full range of engine operation, including at part-load and high-load conditions.

The program team projected that in the 2020–2025 timeframe, spray-guided DI will be the mainstream DI technology in use, supplanting wall guided DI. Spray-guided DI offers the capability to deliver a stratified charge—where the fuel concentration decreases away from the spark plug—that will facilitate lower GHG emissions through lean-burn operation.

For diesel engines, emissions requirements will cause the injection pressures to continue to increase to the 2000–2400 bar injection pressure range. These very high injection pressures support better combustion and reduced engine-out emissions. In addition, multiple injection events will be used to better control the onset and progress of the combustion event in the cylinder.

4.1.3 Boosting System

Using devices to boost the engine's intake pressure will increase the torque and power available from a given engine displacement. By increasing the boost pressure while decreasing engine displacement, the power level is maintained while reducing pumping work in the engine through shifting engine operation to higher-load operating points.

The advanced engines in the 2020–2025 timeframe are expected to have advanced boosting systems to increase the pressure of the intake charge. Various boosting approaches are possible, such as superchargers, turbochargers, and electric motor-driven compressors and turbines. The appropriate technology for 2020–2025 will need to provide cost-effective improvement in performance and efficiency while mitigating turbo lag.

Turbocharged engines in the 2020–2025 timeframe are expected to have an advanced boost strategy that mitigates turbo lag while providing a smooth acceleration feel.

The advanced engines with boost systems were assumed to have two-stage series sequential turbocharger systems. Turbocharging means that there is some risk of the vehicle performance being affected by turbo lag, a delay in the torque rise that results from the dynamics of the gas flow through the engine. Turbo lag is most significant during hard acceleration events, especially when the engine starts at or near its idle speed and load. Mitigating turbo lag means carefully choosing the capacities of the high pressure and low pressure compressors and turbines and connecting pipes to provide acceptable steady-state torque across the engine speed range and an acceptable transient rate of torque rise, often expressed as the time required to reach 85% of maximum torque at a given engine speed. Modeling turbo-lag effects is described in Section 6.3, below.

4.1.4 Other Engine Technologies

Other engine technologies incorporated into the future engines were further improvements in engine friction leading to a global reduction in engine fuel consumption. This friction reduction is expected to result from a combination of technology advances, including piston ringpack, bore finish, lower-viscosity crankcase lubricants, low-friction coatings, valvetrain components, and bearing technology. The details of these improvements in engine friction were not explicitly itemized in this study, and were instead treated as a global engine friction reduction.

Another approach is to optimize the overall engine design, for example, by combining engine components to reduce mass and thermal inertia, giving an improved package and faster warm-up. Ancillary systems may also be electrified to remove the front engine accessory drive (FEAD) and allow variable accessory performance independent of engine speed. (See, for example, Section 4.5.2, Electric Power Assisted Steering.) The combination of components, such as the exhaust manifold and cylinder head design, should improve the response time for turbocharging and aftertreatment warm-up. Electrification of FEAD components, such as the electrical coolant pump, oil pump, or AC compressor, reduces parasitic losses on the engine and allows accessory operation to be optimized for the operating point independently of the engine.

4.2 Engine Configurations

Several engine configurations were defined using combinations of the advanced engine technologies described in Section 4.1 based on an assessment of what would be in mainstream use in the 2020–2025 timeframe. Five main types of engines were used in the study, and are described in this section.

The engines considered for the 2020–2025 timeframe were developed using two main methods. The first method, used with the boosted SI engines, was to review the reported performance of current research engines, and assume that these current research engines would closely resemble the production engines of the 2020–2025 timeframe. With this approach, current research engines would be refined to meet production standards, including manufacturability, cost, and durability. The second method, used with the Atkinson and diesel engines, was to begin with current production engines and determine a pathway of technology improvements over the next 10–15 years that would lead to an appropriate engine configuration for the 2020–2025 timeframe. With both methods, current trends in engine design and development were extrapolated to obtain an advanced concept performance for the 2020–2025 timeframe that should be achievable in production volumes.

The combinations of technologies encompassed in each advanced engine concept provide benefits to the fueling map, or values of brake-specific fuel consumption (BSFC) over the operating speed and load ranges of each engine. For these future engines, the BSFC is improved by up to 10%. Many of the engine concepts have low BSFC values over large zones of the engine operating map, with the best BSFC point often at part-load conditions when at lower speeds.

4.2.1 Stoichiometric DI Turbo

The basic advanced engine configuration is the Stoichiometric DI Turbo SI engine. This advanced engine assumes continued use of a stoichiometric air-fuel ratio for simplified aftertreatment using a three-way catalyst. The engine modeled has a peak brake mean effective pressure (BMEP) of 25–30 bar, which supports significant downsizing compared to current 2010 engines. This high BMEP level is reached through a combination of engine technologies, including advanced valve actuation, such as CPS; spray-guided DI; and advanced boost systems, such as series-sequential turbochargers (see Sections 4.1.1, 4.1.2, and 4.1.3, respectively).

Current research engines of this configuration have been developed by several groups. One example is the Sabre engine described by Coltman, *et al*. (2008) and by Turner, *et al*. (2009). MAHLE have also developed a Stoichiometric DI Turbo SI engine, described by Lumsden, *et al*. (2009).

The future engine configuration was assumed to use a cooled exhaust manifold to keep the turbine inlet temperatures below 950°C over the full operating range of the engine to mitigate the need for upgraded materials in the exhaust manifold and turbine to accommodate higher exhaust gas temperatures. This design change allows the engine to operate with a stoichiometric air-fuel ratio over the complete operating map, even at high-speed, high-load operating conditions, which significantly improves the fuel consumption in this part of the operating map.

4.2.2 Lean-Stoichiometric Switching

The Lean-Stoichiometric DI Turbo SI engine configuration is similar in all respects to the Stoichiometric DI Turbo engine described above in Section 4.2.1, except that it uses a fuel-lean air-fuel ratio at moderate speeds and loads, such as those seen on the FTP75 cycle. Elsewhere, such as on the US06 cycle, the engine switches to stoichiometric operation to avoid exceeding the lean aftertreatment temperature limits. This mixed-mode operation allows the engine to take advantage of the efficiency benefits of lean operation while mitigating the technical challenges associated with lean-burn emissions control.

Fuel lean operation improves fuel consumption by increasing the relative charge volume per unit of fuel burned. Nevertheless, lean operation leads to significant increases in engine-out nitrogen oxides (NO_x) compared to stoichiometric operation, and therefore requires additional emissions control systems to remove NO_x from net oxidizing exhaust gas, such as a lean NO_x trap (LNT) or a urea-based selective catalytic reduction (SCR) system. The program team raised concerns about the effectiveness of these NO_x removal systems at the high temperatures and exhaust gas flow rates, or space velocities, easily reached by SI engines at high engine speed or load, and also about catalyst durability under hot and oxidizing conditions over the vehicle life. These concerns suggest that meeting criteria pollutant levels over a drive cycle such as the US06 could be challenging to the expected end of life, but advances would be made over the intervening years to make such systems production feasible.

Therefore, the engine switches to stoichiometric operation when the exhaust temperature crosses a threshold above which the NO_x removal system catalysts would suffer accelerated degradation. At high load conditions, the exhaust emissions are treated using typical three-way catalysts. The engine therefore performs exactly like the Stoichiometric DI Turbo engine at higher load, but has improved BSFC at lower load because it switches to lean operation. A modest fuel consumption penalty is applied over each drive cycle to account for the use of fuel or other reducing agent to remove NO_x during lean operation.

4.2.3 EGR DI Turbo

The EGR DI Turbo engine is also similar to the Stoichiometric DI Turbo Engine described in Section 4.2.1, except that it uses cooled external exhaust gas recirculation (EGR) to manage in-cylinder combustion and exhaust temperatures. The recirculated exhaust gas dilutes the air and fuel charge in the cylinder, thereby moderating the temperature during combustion and allowing operation without enrichment over the complete operating map. Additionally, the EGR reduces the need for throttling at low-load operation, reducing engine pumping losses.

Dual high-pressure and low-pressure EGR loops were assumed for this engine configuration, which will require additional components such as EGR valves and a heat exchanger (EGR cooler) to manage the EGR flow and temperature. EGR allows a modest overall improvement in fuel consumption across the complete operating map compared to the Stoichiometric DI Turbo engine.

4.2.4 Atkinson Cycle

The Atkinson cycle is characterized by leaving the intake valves open during the start of the compression stroke, which lowers the effective compression ratio of the engine back to that of the normal SI engine, but allows for a larger effective expansion ratio. This change in engine operation improves fuel consumption, but penalizes torque availability at lower engine speeds. For this reason, Atkinson cycle engines are typically used only in hybrid vehicle applications, where the electric machine can be used to provide extra torque during launch or other hard acceleration events.

Separate Atkinson cycle engine fueling maps were developed for the 2020–2025 timeframe with both CPS and DVA valvetrains. These engines are only used with the P2 parallel and Input Powersplit hybrid powertrains described in Section 4.3. The torque curve and fueling map thus generated also reflect so-called downspeeding, or a lower overall operating speed range, which yields further fuel consumption benefits by reducing frictional losses in the engine.

4.2.5 Advanced Diesel

The advanced diesel engines for the 2020–2025 timeframe were developed by starting with existing production engines and identifying technology advances that would lead to further improvements in fuel consumption. These technologies include many of the ones discussed in Section 4.1, as applied to diesel engines.

This approach led to different maps being developed for each of the vehicle classes that had diesel engines available: the Small Car, Full Size Car, Large MPV, LDT, and LHDT. For example, the LHDT engine torque curve and fueling maps were generated by starting with a 6.6 L diesel engine typical for this class and applying the benefits of improvements in pumping losses or friction to the fueling map. Engine displacements for the advanced diesels were chosen based on the current torque and power levels available from these engines, the expected future requirements, and the effects of applying advanced technologies to support further downsizing, for example. Current diesel engines for LDVs already use advanced variable-geometry boost systems and high-pressure common-rail direct injection for better torque response and specific power. Improvements in these areas are therefore expected to be incremental, by contrast with the more extensive changes to SI engine architectures described above. For example, the peak BMEP of the advanced diesels is in the 17–23 bar range, which is noticeably lower than that expected for the advanced SI engines. This difference is, however, consistent with Ricardo's expectation of the pace and direction of technology development for diesel engines that comply with the expected emissions requirements defined in the study's ground rules defined in Section 3.2.

4.3 Hybrid Technologies

The selection of hybrid technology for a vehicle is complex, with an engineering trade-off between fuel consumption benefit and system complexity and cost. As hybrid vehicle market share continues to grow, consumers will have a range of choices.

A wide range of hybrid configurations were considered in the initial part of the program, with the program studying three main approaches: micro hybrid (stop-start), P2 parallel, and Input Powersplit. For this study, it was assumed that the hybrid powertrain configurations will be studied in all but the LHDT vehicle class.

4.3.1 Micro Hybrid: Stop-Start

The most basic hybridization method shuts off the engine during idle periods, and typically uses an enhanced starter motor and limited use of driver comfort features during engine off, such as the radio and some heat but not air conditioning. This approach reduces fuel use over city drive cycles by minimizing idling, but provides no benefit for highway driving or when air conditioning is requested.

The stop-start, micro hybrid approach is the lowest-cost hybrid system, and can be implemented relatively quickly on most vehicles on the market today. Stop-start systems are already in production and the technology is maturing. Further development will lead to increased user acceptance, for example, through transparent integration with low impact on vehicle performance or noise, vibration, and harshness (NVH).

The program team has assumed that by the 2020–2025 timeframe, all vehicles with an otherwise conventional powertrain will have stop-start functionality implemented. For the vehicle models in this study, the starter motor does not provide motive power, but is capable of recovering enough energy to offset accessory loads.

4.3.2 P2 Parallel Hybrid

The P2 Parallel Hybrid powertrain places an electric machine on the transmission input, downstream of the engine clutch. This system allows stop-start, electrical launch, launch assist, and regenerative braking functionality. The clutch also allows the engine to be decoupled from the rear of the driveline, allowing pure electric propulsion, or electric vehicle (EV) mode operation. This wide application of electrical power in a variety of vehicle operating conditions facilitates downsizing the engine from that in the comparable conventional vehicle.

This hybrid powertrain is expected to significantly reduce GHG emissions, especially during city driving. Highway driving fuel consumption is expected to improve because the electric machine in the P2 hybrid allows for a smaller, more efficient internal combustion engine to be used. This smaller engine, however, may limit vehicle performance in situations requiring continuous engine power, such as a sustained hill climb.

P2 Parallel hybrids are in limited production currently, including such vehicles as the Hyundai Sonata, the Porsche Cayenne, and the Volkswagen Touareg. Prototypes have also been built by various companies using existing off-the-shelf components.

A P2 Parallel Hybrid system can be used with an automatic transmission, automated manual transmission (AMT), continuously variable transmission (CVT), or dual clutch transmission (DCT). Hellenbroich and Rosenburg (2009) describe a P2 variant with AMT, for example. For this program, the P2 Parallel Hybrid powertrain was modeled using the DCT, which has fixed gear ratios and no torque converter.

4.3.3 Input Powersplit

The simplest Powersplit hybrid configuration replaces the vehicle’s transmission with a single planetary gearset and two electrical machines connected to the planetary gearset. The planetary gearset splits engine power between the mechanical path and the electrical path to achieve a continuously variable transmission. In some Input Powersplit configurations, a second planetary gearset is used to speed up one of the electrical machines; however, the CVT functionality is still retained. The Toyota Prius and the Ford Hybrid Escape are two examples of Input Powersplit hybrid vehicles currently sold in the United States.

With the appropriate electric accessories, the Input Powersplit system allows for EV mode operation, as well as stop-start operation, electric launch, launch assist, and regenerative braking. In addition, the system allows for engine downsizing to help reduce fuel consumption, even though the smaller engine may limit vehicle performance in situations requiring continuous engine power, such as a sustained hill climb. The Powersplit system provides significant improvements in fuel consumption in city driving. During highway cycles, the benefits of regenerative braking and engine start-stop are reduced, however, the CVT feature of the engine helps during the highway cycle as the engine is kept at an efficient operating point.

4.4 Transmission Technologies

The U.S. vehicle market is currently dominated by automatic transmissions, with a development emphasis on increasing the launch-assist device efficiency and on increasing the number of gear ratios to allow the engine to operate more frequently in regions of high efficiency. Nevertheless, dual clutch transmissions (DCT) are expected to be adopted over the next 10 to 15 years because of their potential to further improve fuel economy and maintain drivability. CVTs tend to have higher friction than DCTs and provide a different driving experience than stepped transmissions. CVTs were not included in the scope of this study, even though they are a current production technology.

The development of DCT technology is expected to be implemented in the U.S. based on experience with European and Japanese applications. Some vehicles with DCTs are entering volume production, such as the Ford Fiesta, Ford Focus, and VW Passat. Automatic transmissions also continue to be developed and refined, with new technologies being implemented in luxury vehicles and cascading down to other vehicle classes. Given that 94% of current U.S. transmissions are automatics, efficiency improvements that mitigate GHG emissions are expected to come from the following:

- Increased gear count from 4–6 currently to 7 or 8 by 2020–2025
- Improved kinematic design
- Component efficiency improvement or alternative technologies
- Launch devices
- Dry sump technology

The various base transmission technologies are described, followed by launch device options, and, finally, other technologies expected to improve transmission efficiency. The effects of these various technologies on transmission efficiency were incorporated into the models.

4.4.1 Automatic Transmission

The automatic transmission is hydraulically operated, and uses a fluid coupling or torque converter and a set of gearsets to provide a range of gear ratios. Viscous losses in the torque converter decrease the efficiency of the automatic transmission. For the study timeframe, it was assumed that eight-speed automatic transmissions will be in common use, as this supports more efficient operation. The Small Car is an exception, and was assumed to only have enough package space to support a six-speed transmission. For the 2020–2025 timeframe, losses in advanced automatic transmissions are expected to be about 20–33% lower than in current automatic transmissions from the specific technologies described below. Additional benefits will be realized by having more gear ratios available to help maintain the engine near its best operating condition.

4.4.2 Dual Clutch Transmission (DCT)

The DCT has two separate gearsets operating in tandem, one with even gears and the other with odd. As the gear changes, one clutch engages as the other disengages, thereby reducing torque interrupt and improving shift quality, making it more like an automatic transmission. The DCT, however, does not require a torque converter which improves its efficiency compared to an automatic transmission, and may use either wet or dry type launch clutches. For the 2020–2025 timeframe, energy losses in both wet clutch and dry clutch DCTs are expected to be 40–50% lower than in current automatic transmissions. Additional benefits will be realized by having more gear ratios available to help keep the engine near its best operating condition.

4.4.3 Launch Device: Wet Clutch

A wet clutch provides torque transmission during operation by means of friction action between surfaces wetted by a lubricant. The lubricant is required for cooling during gear shifts when the clutch is slipping in larger LDV classes. As a secondary lubrication system is needed for the actuation requirements, wet clutch systems are expected to be heavier, cost more, and be less efficient than dry clutch systems.

By the 2020–2025 timeframe, wet clutch DCTs are expected to develop into so-called damp clutch DCTs, since it approaches the efficiency of a dry clutch with the longevity and higher torque capacity of a wet clutch. In damp clutch DCTs, a limited spray is applied to cool the clutch materials. A damp clutch requires a lubrication system but is more efficient due to improved control, leading to reduced windage and churning losses.

4.4.4 Launch Device: Dry Clutch Advancements

The standard dry clutch requires advanced materials to dissipate heat and prevent slipping. The thermal load resulting from engagement prevents dry clutches from being used in high torque and heavy duty cycle applications, even though they are more efficient since they significantly reduce parasitic shear fluid losses and do not require an additional lubrication system. The GHG emissions benefit of a dry clutch over a wet clutch should be realized at launch and during transient driving, thus primarily for city driving. Advancements in materials or electric assist could enable this technology to be used in larger LDVs and more severe duty cycles by the study timeframe, but is generally assumed to be prevalent in the smaller vehicle classes.

4.4.5 Launch Device: Multi-Damper Torque Converter

Dampers added to the torque converter enable a lower lockup speed, therefore decreasing the more fuel-intensive period of hydrodynamic power transfer. Multi-damper systems provide earlier torque converter clutch engagement; however, drivability and limited ratio coverage have limited the deployment of this technology to date. The technology must be integrated during transmission design. The GHG emissions benefit should come from reduced slippage and smoother shifting.

4.4.6 Shifting Clutch Technology

Shift clutch technology improves the thermal capacity of the shifting clutch to reduce plate count and lower clutch losses during shifting. Reducing the number of plates for the shifting process and reducing the hydraulic cooling requirements will increase the overall transmission efficiency for similar drivability characteristics. Technology deployment has been limited by industry prioritization of drivability over shift efficiency, especially since shift events are a very small portion of typical driving. The technology will be best suited to smaller vehicle segments because of reduced drivability expectations—this technology may not be suitable for higher torque applications.

4.4.7 Improved Kinematic Design

Improved kinematic design uses analysis to improve the design for efficiency by selecting the kinematic relationships that optimize the part operational speeds and torques. Large improvements in efficiency have been noted for clean sheet designs for six-speed and eight-speed transmissions. This approach will provide a GHG emissions benefit across all vehicle classes and operating conditions.

4.4.8 Dry Sump

A dry sump lubrication system provides benefits by keeping the rotating members out of oil, which reduces losses due to windage and churning. This approach will provide a GHG emissions benefit across all vehicle classes, with the best benefits at higher speeds.

4.4.9 Efficient Components

A continuous improvement in seals, bearings and clutches all aimed at reducing drag in the system should provide GHG emissions benefits without compromising transmission performance.

4.4.10 Super Finishing

This technology approach chemically treats internal gearbox parts for improved surface finish. The improved surface finish reduces drag which increases efficiency.

4.4.11 Lubrication

New developments in base oils and additive packages will reduce oil viscosity while maintaining temperature requirements, thereby improving transmission efficiency.

4.5 Vehicle Technologies

Several vehicle technologies were also considered for the study to the extent that they help support future ranges of vehicle mass, aerodynamic drag, and rolling resistance for each of the vehicle classes in the study.

Technologies considered include mass reduction through use of advanced materials with a higher strength to mass ratio and through consolidation and optimization of components and systems. Aerodynamic drag is expected to see improvements through adoption of both passive and active aerodynamic features on vehicles in the 2020–2025 timeframe. Continued improvement in tire design is expected to reduce rolling resistance and thereby provide a benefit to fuel consumption.

In addition, vehicle accessory systems such as the cooling pumps and power steering systems are expected to become electrified by the 2020–2025 timeframe. These electrified accessories should reduce the power required to keep them active, which will also improve fuel consumption, and are described in greater detail below.

4.5.1 Intelligent Cooling Systems

Intelligent cooling systems use an electric coolant pump to circulate engine coolant, removing the power required for this pump from the FEAD. Removing the coolant pump from the FEAD also enables independent pump speed control. Rather than running at a fixed multiple of the engine speed, the coolant pump can spin at the appropriate speed for the current cooling requirements. Standard cooling systems are sized to provide cooling at maximum load and ambient conditions, but most vehicles only rarely operate under these extreme conditions. Intelligent cooling also enables quicker warm-up of the engine by controlling coolant flow. This reduces engine friction by increasing engine temperature during the warm up process.

Ricardo estimates this technology will lower fuel consumption over the FTP cycle. BMW is implementing this technology on their twin-turbo 3-L inline-6 cylinder engine, introduced in 2007 in their 335i model. This technology is projected to be readily available by the 2020–2025 timeframe.

4.5.2 Electric Power Assisted Steering

Electric Power Assisted Steering (EPAS) uses either rack or column-drive electric motors to assist driver effort instead of a hydraulic power assist system. EPAS replaces the engine-driven hydraulic pump, hydraulic hoses, fluid reservoir, fluid, and hydraulic rack. The efficiency of this system is a result of reduced FEAD losses and improved energy management that comes from decoupling the load from the engine. This technology is currently available for small and medium sized passenger vehicles, and it is likely that this will be commercially available for LDVs up to the LDT class by the 2020–2025 timeframe. This technology is required for vehicles with any electrical launch or EV mobility, so that the vehicle can be steered during EV mode.

5. TECHNOLOGY BUNDLES AND SIMULATION MATRICES

The program team and external stakeholders bundled the technologies described in Section 4, "Technology Review and Selection," into a set of technology packages to be evaluated in the seven LDV classes described in Section 2.2, "Ground Rules for Study". These LDV classes are Small Car, Standard Car, Small MPV, Full Size Car, Large MPV, LDT, and LHDT.

5.1 Technology Options Considered

Definitions of the hybrid powertrain, engine, and transmission technology options are presented in Tables 5.1–5.4. The engine technologies are defined in Table 5.1; hybrids, in Table 5.2; and transmissions, in Table 5.3. Many of the engines in Table 5.1 use some measure of internal EGR, but for this table "Yes" means significant EGR flow through an external EGR system. All of the advanced transmissions in Table 5.3 include the technologies described in Section 4.4, including dry sump, improved component efficiency, improved kinematic design, super finish, and advanced driveline lubricants.

Table 5.1: Engine technology package definition.

Engine	Air System	Fuel Injection	EGR	Valvetrain CPS	Valvetrain DVA
2010 Baseline	NA	PFI	No	No	No
Stoich DI Turbo	Boost	DI	No	Yes	No
Lean-Stoich DI Turbo	Boost	DI	No	Yes	No
EGR DI Turbo	Boost	DI	Yes	No	No
Atkinson	NA	DI	No	Yes	Yes
Diesel	Boost	DI	Yes	Yes	No

Table 5.2: Hybrid technology package definition.

Function	Powertrain Configuration 2010 Baseline	Stop-Start	P2 Parallel	Powersplit
Engine idle-off	No	Yes	Yes	Yes
Launch assist	No	No	Yes	Yes
Regeneration	No	No	Yes	Yes
EV mode	No	No	Yes	Yes
CVT (Electronic)	No	No	No	Yes
Power steering	Belt	Electrical	Electrical	Electrical
Engine coolant pump	Belt	Belt	Electrical	Electrical
Air conditioning	Belt	Belt	Electrical	Electrical
Brake	Standard	Standard	Blended	Blended

Table 5.3: Transmission technology package definition.

Transmission	Launch Device	Clutch
Baseline Automatic	Torque Converter	Hydraulic
Advanced Automatic	Multidamper Control	Hydraulic
Dry clutch DCT	None	Advanced Dry
Wet clutch DCT	None	Advanced Damp

5.2 Vehicle configurations and technology combinations

Vehicles were assessed using three basic powertrain configurations: conventional stop-start, P2 hybrid, and Input Powersplit hybrid. Each vehicle class considered in the study was modeled with a set of technology options, as shown in Tables 5.4 and 5.5. Each of the 2020 engines marked for a given vehicle class in Table 5.4 was paired with each of the advanced transmissions marked for the same vehicle class.

Table 5.4: Baseline and Conventional Stop-Start vehicle simulation matrix.

			Advanced Engine				Advanced Transmission				
Vehicle Class	Baseline Engine & 2010 6-Speed Automatic Trans.	2010 Diesel & 2010 6-Speed Automatic Transmission	Stoich DI Turbo with CPS	Lean DI Turbo with CPS	EGR DI Turbo with CPS	2020 Diesel	6-Speed Automatic	6-Speed Dry DCT	8-Speed Automatic	8-Speed Dry DCT	8-Speed Wet DCT
Small Car	X		X	X	X	X	X	X			
Standard Car	X		X	X	X				X	X	
Small MPV	X		X	X	X				X	X	
Full Size Car	X		X	X	X	X			X	X	
Large MPV	X		X	X	X	X			X		X
LDT	X		X	X	X	X			X		X
LHDT	X	X	X	X	X	X			X		X

Parameter	DoE Range (%)	
Engine Displacement	50	125
Final Drive Ratio	75	125
Rolling Resistance	70	100
Aerodynamic Drag	70	100
Mass	60	120

Table 5.5: P2 and Input Powersplit hybrid simulation matrix.

Vehicle Class	Hybrid Architecture: P2 Hybrid with 2020 DCT	Hybrid Architecture: Input Powersplit	Advanced Engine: Stoich DI Turbo with CPS	Advanced Engine: Lean DI Turbo with CPS	Advanced Engine: EGR DI Turbo with CPS	Advanced Engine: Atkinson with CPS	Advanced Engine: Atkinson with DVA
Small Car	X	X	X	X	X	X	X
Standard Car	X	X	X	X	X	X	X
Small MPV	X	X	X	X	X	X	X
Full Size Car	X	X	X	X	X	X	X
Large MPV	X	X	X	X	X	X	X
LDT	X		X	X	X	X	X
LHDT							

Parameter	DoE Range (%) P2 Hybrid		DoE Range (%) Powersplit	
Engine Displacement	50	150	50	125
Final Drive Ratio	75	125	75	125
Rolling Resistance	70	100	70	100
Aerodynamic Drag	70	100	70	100
Mass	60	120	60	120
Electric Machine Size	50	300	50	150

6. VEHICLE MODEL

Vehicle models were developed to explore the complete design space defined by the technologies, vehicle classes, and powertrain architectures included for the 2020–2025 timeframe. The modeling process started by developing baseline models to compare against data for current (2010) vehicles. A detailed comparison between baseline model results and vehicle test data were used to validate the models.

6.1 Baseline Conventional Vehicle Models

For each of the seven LDV classes considered in this project, vehicle models were developed for a 2010 baseline case. Each LDV class was assigned a representative vehicle for the purposes of establishing a baseline against known vehicle data.

A complete, physics-based vehicle and powertrain system model was developed and implemented in MSC.Easy5™. MSC.Easy5™ is a commercially available software package widely used in industry for vehicle system analysis, which models the physics in the vehicle powertrain during a drive cycle. Torque reactions are simulated from the engine through the transmission and driveline to the wheels. The model reacts to simulated driver inputs to the accelerator or brake pedals, thus enabling the actual vehicle acceleration to be determined based on a realistic control strategy. The model is divided into a number of subsystem models. Within each subsystem the model determines key component outputs such as torque, speeds, and heat rejection, and from these outputs, appropriate subsystem efficiencies can be calculated or reviewed as part of a quality audit.

The seven vehicle classes considered in this study are shown in Table 6.1, along with the baseline vehicles for each class. Each of the baseline exemplar vehicle models had vehicle-specific vehicle, engine, and transmission model parameters. The models were exercised over the FTP75 and HWFET fuel economy drive cycles, and the results compared with the EPA Vehicle Certification Database (Test Car List) fuel economy data for each of the baseline exemplar vehicles.

Table 6.1: Vehicle classes and baseline exemplar vehicles.

Vehicle Class	Baseline Exemplar
Small car	Toyota Yaris
Standard car	Toyota Camry
Small MPV	Saturn Vue
Full sized car	Chrysler 300
Large MPV	Dodge Grand Caravan
LDT	Ford F150
LHDT	Chevy Silverado 3500HD

6.2 Baseline Hybrid Vehicle Models

For each hybrid technology, Ricardo developed a baseline model to calibrate the hybrid control strategy and vehicle, engine, and driveline parameters. As with the conventional vehicles described in Section 6.1, a full physical model of each baseline hybrid exemplar vehicle was developed and implemented in MSC.Easy5™. The hybrid control algorithms are also implemented in the respective MSC.Easy5™ models.

The vehicles were modeled using published information from various sources and Ricardo proprietary data. Each of the baseline exemplar hybrid vehicle models had vehicle-specific vehicle, engine, and transmission model parameters. The exemplar hybrid vehicles are listed in Table 6.2, along with the exemplar used to confirm the DCT powertrain.

Table 6.2: Advanced powertrain configurations and baseline exemplar vehicles.

Powertrain Configuration	Exemplars
DCT (conventional)	Audi A3 / VW Passat
P2 Hybrid	Hyundai Sonata Hybrid
Input Powersplit	Ford Escape Hybrid

6.3 Engine Models

The engines considered in the design space are defined by their torque curve, fueling map, and other input parameters. For the 2010 baseline vehicles, the engine fueling maps and related parameters were developed for each specific baseline exemplar vehicle. For the engines used in the 2020–2025 vehicles, reference engine models were developed and scaled to each of the LDV classes.

As described in Section 4.2, the program used two methods to develop the engine models for the 2020–2025 timeframe. The first was to look at the reported performance of current research engines, and assume that these current research engines would closely resemble the production engines of the 2020–2025 timeframe. With this method, current research engines would be refined to meet production standards, including manufacturability, cost, and durability. The second method was to begin with current production engines and determine a pathway of technology improvements over the next 10–15 years that would lead to an appropriate engine configuration for the 2020–2025 timeframe.

The fueling maps and other engine model parameters used in the study were based on published data and Ricardo proprietary data. These initial maps were developed into a map reflecting the effects on overall engine performance of the combination of the future technologies considered. Each proposed map was reviewed and approved by EPA and the Advisory Committee. This process was repeated for each of the engine technologies included in the simulation matrix, as shown in Tables 5.4 and 5.5 for conventional stop-start and hybrid powertrain configurations, respectively.

Engine downsizing effects were captured by changing the engine displacement in the given vehicle. This approach assumes that the downsized engines have the same brake mean effective pressure (BMEP), which scales the engine's delivered torque by the engine swept volume, or displacement. The BSFC of the scaled engine map is also adjusted by a factor that accounts for the change in heat loss that comes with decreasing the cylinder volume, and thereby increasing the surface to volume ratio of the cylinder. The minimum number of cylinders in an engine was set to three, and the minimum per-cylinder volume, to 0.225 liters. These constraints established the minimum engine displacement in the design space to 0.675 liters.

Engine efficiency is therefore assumed to be a function of engine speed and BMEP, with specific fueling rates (mass per unit time) calculated from the torque. Thus, downsizing the engine directly scales the delivered torque, and the fueling map is adjusted accordingly. The engine speed range was held constant over the engine displacement ranges of interest.

Turbo lag was represented in the model by applying a first order transfer function between the driver power command and the supplied engine power at a given speed. This transfer function was only used during the performance cycle, which is a hard acceleration from a full stop used to assess vehicle acceleration performance. The transfer function approximates the torque rise rate expected in the engines with turbocharger systems during vehicle launch. Adjusting the time constant in the transfer function allowed the acceleration performance to see the effect of turbo lag. A time constant of 1.5 seconds was selected to represent the expected delay in torque rise on the advanced, boosted engines from the spool up of the turbine.

6.3.1 Warm-up Methodology

A consistent warm-up modeling methodology was developed for the study to account for the benefits of an electrical water pump and of warm restart for the advanced vehicles. To account for engine warm-up effects, Ricardo used company proprietary data to develop an engine warm-up profile. This engine warm-up profile is used to increase the fueling requirements during the cold start portion of the FTP75 drive cycle. This correction factor for increased fueling requirements is applied to the fuel flow calculated during the warm-up period in the FTP75 drive cycle.

6.3.2 Accessories Models

Parasitic loads from the alternator were assumed constant over the drive cycles and were included in the engine model. Alternator efficiency was assumed to be 55% for baseline vehicle simulations and 70% for the high efficiency alternator in all of the advanced technology package simulations to represent future alternator design improvements.

Power-assisted steering (PAS) systems—full electric or electric hydraulic—were modeled as being independent of engine speed and were included in the engine model for each baseline vehicle. The EPAS systems assumed no engine parasitic loads on the EPA drive cycles and acceleration performance cycles, which require no steering input. All advanced package simulations included the benefit of EPAS. The LHDT and LDT classes used electric hydraulic PAS, whereas the five smaller vehicle classes used full electric PAS.

The LDT and LHDT models also include engine parasitic losses due to a belt-driven engine cooling fan. The other vehicles were assumed to have electric radiator fans, with the load being drive cycle dependent and added to the vehicle's base electrical load.

Current production cars have begun incorporating advanced alternator control to capture braking energy through electrical power generation. This is done by running the alternator near or at full capacity to apply more load on the engine when the driver demands vehicle deceleration. It is believed that this feature will be widespread in the near future and, hence, the study captures it by incorporating this function into the Conventional Stop-Start model. For 2020 vehicle configurations, the alternator efficiency was increased to 70% to reflect an improved efficiency design. The advanced alternator control strategy monitors vehicle brake events and captures braking energy when available. The control strategy also limits the maximum power capture to 2800 Watts based on the assumption that the advanced alternator is limited to 200 Amps at 14 Volts charging. By integrating power, energy is accumulated from every brake event and when there is available "stored" brake energy, the control strategy switches the parasitic draw from the engine to the battery until the accrued energy is consumed, at which point the load switches back to the engine. For the five smaller LDV classes, both the fan and base electrical loads are included in the advanced charging system as electric fans are employed. The system will only benefit the two truck classes, LDT and LHDT, in terms of base electrical load as these vehicle classes use mechanical fans.

6.4 Transmission Models

Efficiencies for each gear ratio were calculated based on data from several transmission and final drive gear tests. Different efficiency curves were mapped for planetary, automatics, and dual-clutch, with the DCT efficiency modified depending on whether a dry or wet clutch is used. Hydraulic pumping losses were included in the efficiency calculations. Transmission efficiencies were calculated to represent the average of the leading edge for today's industry and not one particular manufacturer's design. Advanced automatic transmission designs are projected to reduce losses by 20–33% from current automatic transmissions. In addition, the advanced automatic transmissions use advanced torque converters, described in Section 6.5, below. Wet clutch DCT efficiencies are also projected to approach current dry clutch DCT efficiencies.

In anticipation of future technology packages, it is expected that some advanced level of transmission shift optimization will be implemented in year 2020–2025 vehicles. For the 2020-2025 Conventional Stop-Start architecture, an advanced transmission option was implemented to determine the most favorable gear for a given driver input and vehicle road load. This approach takes the place of predefined calibration shift maps based on throttle and vehicle speed. These strategies presently cause significant implications for drivability and hence affect consumer acceptability. Nevertheless, it was assumed that by 2020, manufacturers will develop a means of yielding the fuel economy benefit without adversely affecting acceptability.

The advanced transmission shift optimization strategy attempts to keep the engine operating near its most efficient point for a given power demand. In this way, the new shift controller emulates a traditional CVT by selecting the best gear ratio for fuel economy at a given required vehicle power level. Gear efficiency of the desired gear is also taken into account. More often than not, the optimal gear ratio will be between two of the fixed ratios, and the shift optimizer will decide when to shift up or down based on a tunable shift setting. This will enable the shift optimizer to make proper shift decisions based on the type of vehicle and the desired aggressiveness of the shift pattern. To protect against operating conditions out of normal range, several key parameters were identified, such as maximum engine speed, minimum lugging speed, and minimum delay between shifts. For automatic transmissions, the torque converter is also controlled by the shift optimizer, with full lockup only achievable when the transmission is not in 1st gear. During development of this strategy, it was noted that fuel economy benefits of up to 5% can be obtained when compared to traditional shift maps. Figure 6.1 shows a comparison between the shift optimizer strategy and a CVT.

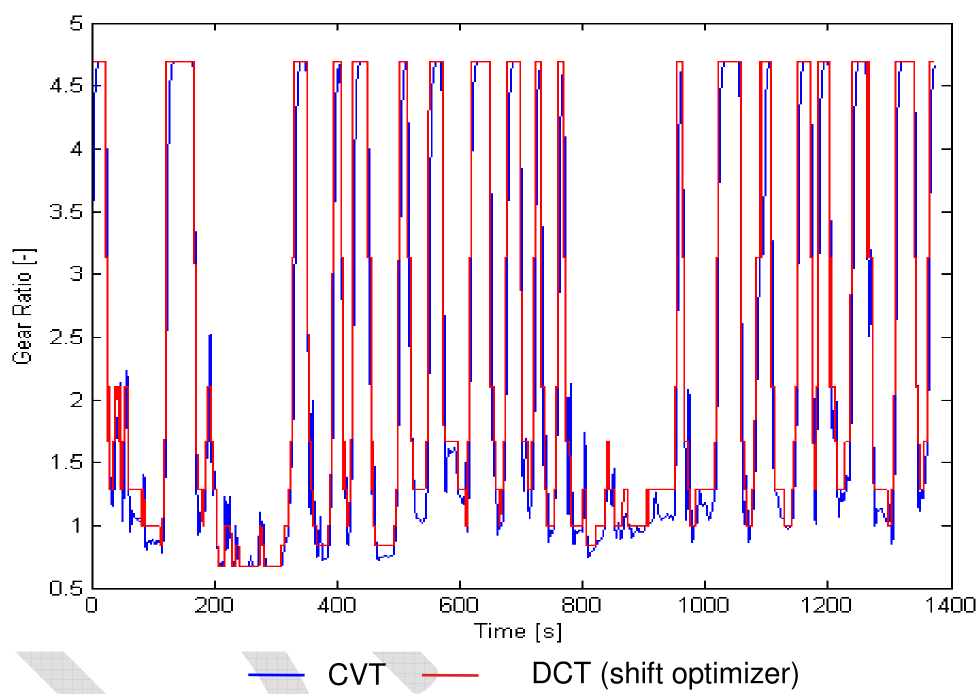

Figure 6.1: Comparison of CVT and optimized DCT gear ratios over drive cycle.

6.5 Torque Converter Models

Torque converter characteristics curves for torque ratio and K-factor were generated using typical industry standards for efficiency. Each vehicle's torque converter characteristics for torque ratio and K-factor were tailored for the application based on Ricardo experience. Impeller and turbine rotational inertias are also input to the model and were estimated based upon Ricardo experience. Vehicle simulations with advanced automatic transmissions include a slight improvement in torque converter efficiency.

A lockup clutch model was used with all torque converters and was of sufficient capacity to prevent clutch slip during all simulation conditions. Lockup was allowed in 3rd and 4th gears with the 4-speed automatics; 3rd, 4th, and 5th gears with the 5-speed automatics; and 4th, 5th, and 6th gears with the 6-speed automatics. During light throttle conditions a minimum engine operating speed of 1400 rpm for I3 engines, 1300 rpm for I4 engines, 1200 rpm for V6 engines, and 1100 rpm for V8 engines with the converter clutch locked was considered in developing the baseline lock/unlock maps. The advanced automatic transmission applications allow torque converter lockup in any gear except first gear.

6.6 Final Drive Differential Model

Baseline final drive ratios were taken from published information and driveline efficiencies and spin losses were estimated based upon Ricardo experience for typical industry differentials. The spin losses of the 4-wheel-drive LDT and LHDT front axle and transfer case were included in the model to capture the fuel economy and performance of the 4-wheel-drive powertrain operating in 2-wheel-drive mode. This approach is similar to the EPA procedure for emissions and fuel economy certification testing.

6.7 Driver Model

The vehicle model is forward facing and has a model for the driver. The driver model applies the throttle or brake pedal as needed to meet the required speed defined by the vehicle drive cycle within the allowed legislative error. This allows the modeling of the actual vehicle response to meet the target drive cycle.

The driver model contains the drive cycle time/velocity trace, controls for the throttle and brake functions and maintains vehicle speed to the desired set point. Vehicle simulations for fuel economy were conducted over the EPA FTP75 (city), HWFET (highway) and US06 drive cycles. The FTP75 cycle consists of three "bags" for a total of 11.041 miles on the conventional vehicles and an additional bag 4 on hybrid vehicles for a total of 14.9 miles. A ten minute engine-off soak is performed between bags 2 and 3 (after 1372 seconds of testing). A bag 1 correction factor is applied to the simulated "hot" fuel economy result of the vehicles to approximate warm-up conditions of increased friction and sub-optimal combustion. The correction factor reduces the fuel economy results of the FTP75 bag 1 portion of the drive cycle by 20% on the current baseline vehicles and 10% on 2020–2025 vehicles that take advantage of fast warm-up technologies.

6.8 Hybrid Models

The hybrid models include all of the conventional vehicle components with the addition (or replacement) of components for electric motor-generators, high voltage battery, high voltage battery controller/bus, transmission, regenerative braking and hybrid supervisory controller. Of these, the critical systems for the model were the electric machines (motor-generators), power electronics, and high-voltage battery system. For each of these systems, current, state of the art technologies were adapted to an advanced, 2020–2025 version of the system, such as by lowering internal resistance in the battery pack to represent 2010 chemistries under development and decreasing losses in the electric machine and power electronics to represent continued improvements in technology and implementation.

In addition, a Ricardo proprietary methodology was used to identify the best possible fuel consumption for a given hybrid powertrain configuration over the drive cycles of interest: FTP, HWFET, and US06. The methodology used the drive cycle profile to identify the features of a control strategy that provide the lowest possible fuel consumption over the drive cycle. The result of this assessment enabled the development of an optimized control system. The simulation results using the hybrid controller were compared against the best case scenario from the methodology to ensure that the hybrid controller in the models is obtaining the most out of the hybrid powertrain.

A key feature of the hybrid controller is that it used a hybrid load following and load averaging strategy to help keep the engine on or near its line of best efficiency on the engine operating map, with some accommodation for the efficiency of the overall powertrain. During low-load conditions, the engine can be made to work harder and more efficiently and to store the excess energy in the battery. In other cases, the energy in the battery can be used to provide launch assist or EV mode driving. All hybrid vehicle simulations were SOC neutral over the drive cycle, so that there is no net accumulation or net depletion of energy in the battery; thus, fuel consumption is an accurate measure of the effectiveness of technologies.

7. MODEL VALIDATION RESULTS

Before executing the DoE simulation matrix, the vehicle models described in Section 6 were validated. Baseline vehicles were modeled, and the simulation results compared against publicly available data on vehicle performance, including acceleration times and fuel economy. Details of the model validation process and results are presented below. In addition, nominal runs were prepared for each major powertrain type to provide a reference point for the input parameters against which to compare the full design space explored in the DoE simulation matrix.

7.1 Baseline Conventional Vehicle Models

Vehicle models were developed for a 2010 baseline case for each of the seven LDV classes. Each LDV class was assigned a representative vehicle for the purposes of establishing a baseline against known vehicle data. Ricardo leveraged the peer-reviewed baseline models from its 2008 study with Perrin Quarles Associates (PQA, now part of SRA) for the five LDV classes from Standard Car through LDT to provide the 2010 baseline case, and to build new baseline models for the Small Car and LHDT classes. The 2010 baseline vehicles use six-speed automatic transmissions and the engines with comparable displacement and peak torque to the exemplar vehicles listed in Table 6.1.

Vehicle performance simulation results are shown in Table 7.1, below, comparing the raw fuel economy results in the EPA Test Car List (EPA, 2010) against the calculated results. The results were considered acceptably close. In addition to the fuel economy tests, the launch performance was also assessed for each of the exemplar vehicles, with particular attention paid to the 0–60 mph acceleration time, as this is readily available for validation. 0–60 mph acceleration times for the exemplar models were within a few tenths of a second of published times for each vehicle.

Table 7.1: Baseline vehicle fuel economy performance.

Vehicle Class	Baseline Exemplars	EPA Test List Fuel Econ (mpg) FTP75	HWFET	US06	Calculated Raw Fuel Econ (mpg) FTP75	HWFET	US06
Small car	Toyota Yaris	38	50	32	40	49	30
Standard car	Toyota Camry	27	42	26	30	44	29
Small MPV	Saturn Vue	24	37	23	24	34	24
Full sized car	Chrysler 300	21	34	21	24	36	24
Large MPV	Dodge Grand Caravan	20	32	21	22	31	21
LDT	Ford F150	16	23	13	16	26	15
LHDT	Chevy Silverado 3500HD (diesel)	—	—	—	16	19	12

7.2 Nominal Runs

Once the models were developed and validated, a series of nominal runs were prepared to assess the accuracy and robustness of the model. The nominal conditions are the reference point for the design space explored by the DoE simulation.

For the conventional vehicles, the nominal condition was calculated using the same vehicle parameter values, such as for mass and aerodynamic drag, as the 2010 baseline vehicles. The advanced engine size was adjusted to match the baseline 0–60 mph acceleration time. For the hybrids, the engine size was reduced 20% from the corresponding conventional nominal size, and the electric machine sized to again match the baseline 0–60 mph acceleration time.

The full table of nominal runs results for the conventional stop/start, P2 hybrid, and Input Powersplit hybrid vehicle combinations is in Appendix 3. These summary results and the rest of the simulation output data were used to assess the quality of the simulation results before executing the DoE simulation matrix, for example, by assessing power flows to and from the battery over the drive cycle.

8. COMPLEX SYSTEMS MODEL (CSM) VALIDATION

CSM is an objective, scientific approach for evaluating several potential options or configurations for benefits relative to each other and to a baseline. For this program, the CSM methodology was used to define the design space for LDVs in the 2020–2025 timeframe, and then to effectively evaluate LDV performance over this large design space.

8.1 Evaluation of Design Space

The purpose of the DoE simulation matrix is to efficiently explore the potential design space for LDVs in the 2020–2025 timeframe. The simulation matrix was designed to generate selected performance results, such as fuel consumption or acceleration times, over selected drive cycles. The DoE approach allows an efficient exploration of the design space while limiting the number of runs needed to survey the design space.

For each discrete combination of vehicle class, powertrain architecture, engine, and transmission in the design space, the continuous input variables were varied over the ranges shown in Tables 8.1 and 8.2 for the conventional and hybrid powertrains, respectively. In the analysis, continuous input variables are evaluated using a combination of the design corner points in a two-level full factorial design and design points within the space based on a Latin hypercube sampling methodology. Note that vehicle mass is considered independently of the combination of discrete technologies; for example, switching from an automatic transmission to a DCT does not automatically adjust the vehicle mass in the simulation.

Table 8.1: Continuous input parameter sweep ranges with conventional powertrain.

Parameter	DoE Range (%)	
Engine Displacement	50	125
Final Drive Ratio	75	125
Rolling Resistance	70	100
Aerodynamic Drag	70	100
Mass	60	120

Table 8.2: Continuous input variable sweep ranges for P2 and Powersplit hybrid powertrains.

	DoE Range (%)			
Parameter	P2 Hybrid		Powersplit	
Engine Displacement	50	150	50	125
Final Drive Ratio	75	125	75	125
Rolling Resistance	70	100	70	100
Aerodynamic Drag	70	100	70	100
Mass	60	120	60	120
Electric Machine Size	50	300	50	150

Latin hypercube sampling is a statistical method originally developed by McKay *et al.* (1979), used to generate a set of parameter values over a multidimensional parameter space. The method randomly samples the multidimensional parameter space in a way that provides comprehensive and relatively sparse coverage for best efficiency. It also allows one to efficiently continue to fill the multidimensional parameter space by further random sampling. It provides more flexibility than traditional multi-level factorial designs for assessing a large parametric space with an efficient number of experiments.

The vehicle simulations were run in batches and the results were collected and processed. Vehicle fuel economy and performance metrics were recorded as well as diagnostic variables such as the total number of gear shifts and the distance traveled during the drive cycle. The data were reviewed using a data mining tool and outliers were analyzed, and, as necessary, debugged and re-run. This approach allowed issues to be detected and diagnosed very quickly within a large amount of data. Once the data were reviewed and approved, response surface models were generated.

8.2 Response Surface Modeling

RSM were generated in the form of neural networks. The goal was to achieve low residuals while not over-fitting the data. Initially, 66% of the data were used for fitting the model while the remainder was used to validate the response surface model's prediction performance. Once a good fit was found, all the data was used to populate the RSM. Each neural network fit contains all of the continuous and discrete variables used in the study for a given transmission. One Neural Network fit per transmission was generated to improve the quality of the fits.

9. RESULTS

The key project results consist of the raw data sets obtained from over 350,000 individual vehicle simulation cases, the Data Visualization Tool developed to query the response surfaces based upon the raw data sets, and this report describing these results. These results are discussed below.

9.1 Basic Results of Simulation

Each of the simulation cases generated data at 10 Hz which allowed evaluation of the performance of a specific vehicle configuration in the design space over each of the drive cycles. These results include parameters such as vehicle speed, calculated engine power, and instantaneous fueling rate. The detailed data from each simulation run were distilled into the main output factors of interest, such as acceleration time and fuel economy, used in the parametric fit of the RSM.

For this study, the main output factors include raw fuel economy and GHG emissions over each of the drive cycles studied and also performance metrics, such as 0–60 mph acceleration times. The complete list of output factors is listed in Appendix 2.

9.2 Design Space Query

The Design Space Query within the Data Visualization Tool allows the user to assess a specific vehicle configuration in the design space by selecting a platform, engine, and transmission and setting the continuous variables within the design space range. The generated performance results are reported in a table that is exportable to Excel. The user can assess multiple vehicle configurations and compare them in Excel. The tool table also allows the user to apply spreadsheet formulas for quick, on-the-side computation. An example of the Design Space Query is shown in Figure 9.1.

9.3 Exploration of the Design Space

A more comprehensive survey of the design space can be conducted using the Design Space Analysis in the Data Visualization Tool, which allows the user to assess the performance of multiple vehicle configurations from a significant portion of the design space simultaneously. Each design is generated by first selecting a vehicle platform, engine, and transmission, and then ranges for the continuous input variables. Figure 9.2 shows the screen where the design space analysis is set up. For each of the continuous variables, values are generated using a Monte Carlo analysis from a uniform distribution over the range selected. These data are stored, and may be exported or plotted.

Once generated, the design points are stored and may be plotted to visualize the tradeoff analysis of the design space. By carefully building a design and varying the parameters, the user can gain an understanding of the effect of each technology and the interactions between technologies. Figures 9.3–9.5 show examples of plots that compare two design space analyses. In these cases, the red points are for a Full Size Car with advanced diesel engine and dry-clutch DCT, whereas the blue points are for a Full Size Car with stoichiometric DI turbo engine and automatic transmission. The black point is the 2010 baseline value. For these examples, the engine displacement was varied from 50% to 125% of nominal, or 0.71 to 1.8 L displacement for the stoichiometric DI turbo engine and 1.4 to 3.6 L for the diesel, and the vehicle mass, from 70% to 100% of nominal, or 2800 to 4000 kg.

The example in Figure 9.6 compares various configurations of the Standard Car, all with the EGR DI Turbo engine but with different powertrains. The two Conventional Stop-Start cases have the advanced eight-speed automatic and dry-clutch DCT, shown in blue and gray, respectively. The Powersplit hybrid is shown in green, and the P2 Hybrid, in red. Again, the black point is the 2010 baseline value.

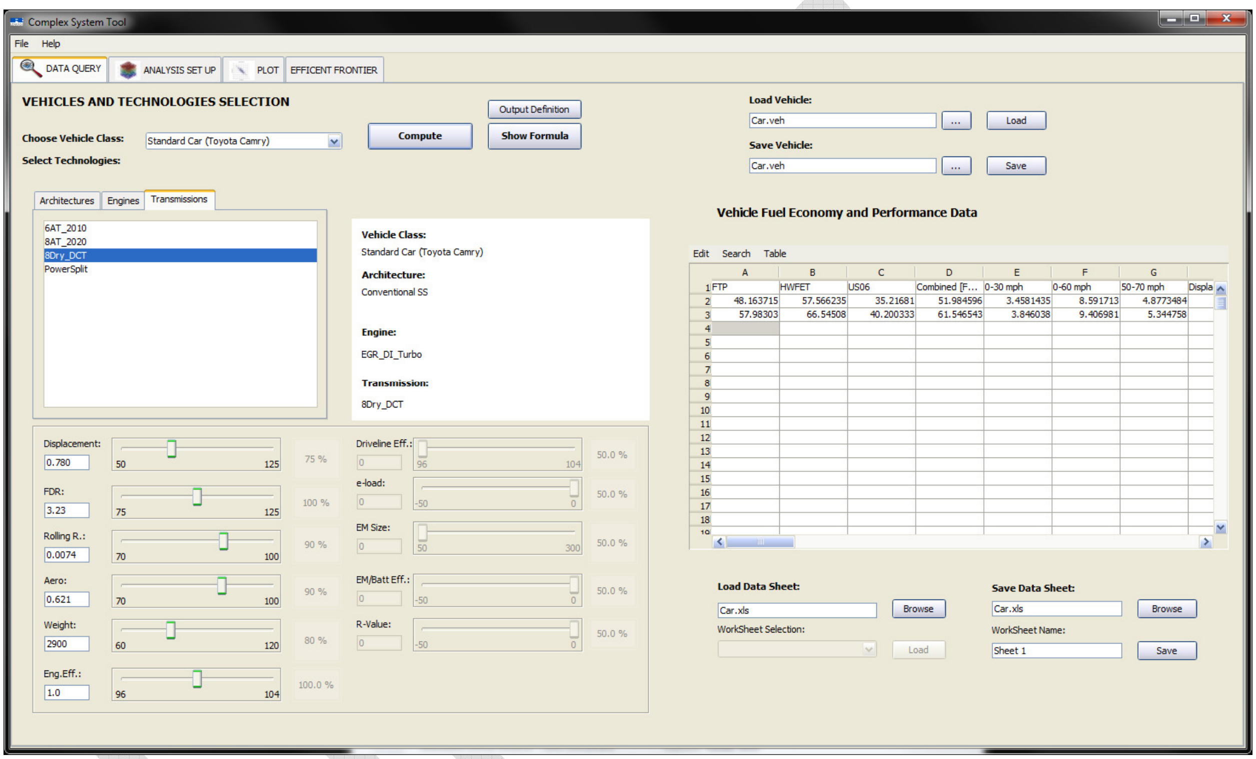

Figure 9.1: Design Space Query screen in Data Visualization Tool.

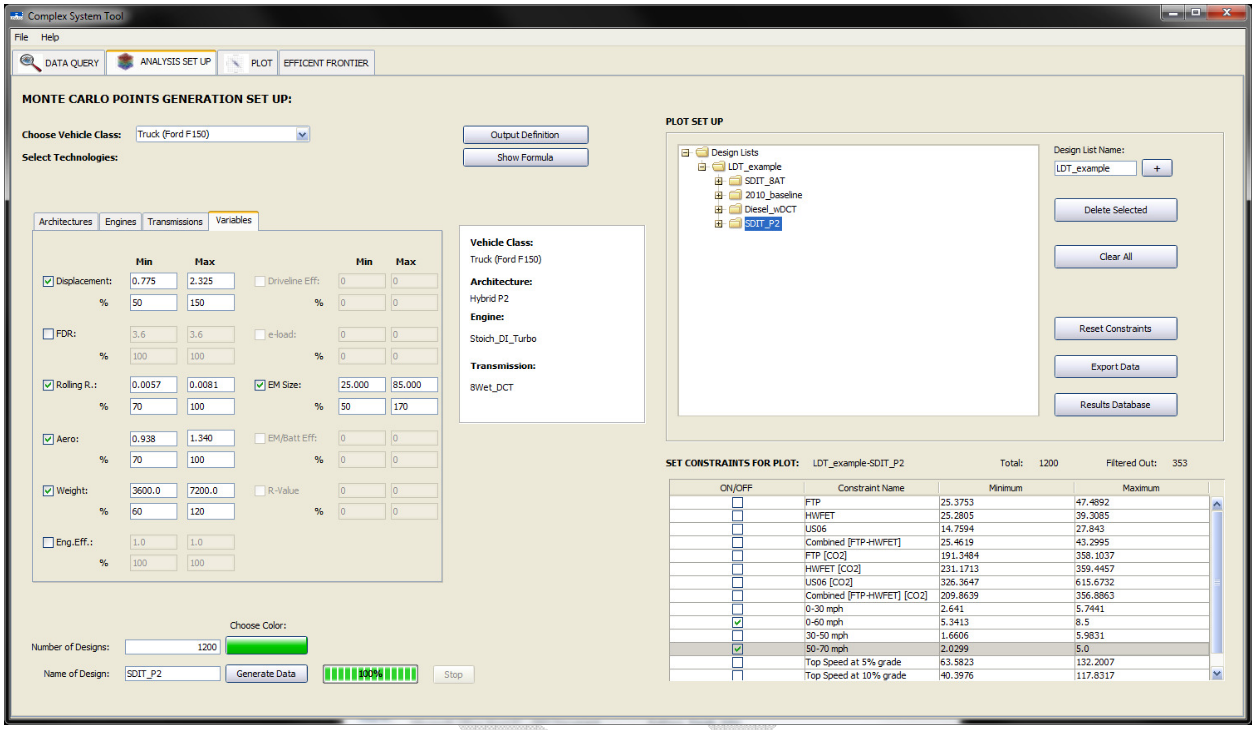

Figure 9.2: Design Space Analysis screen in Data Visualization Tool.

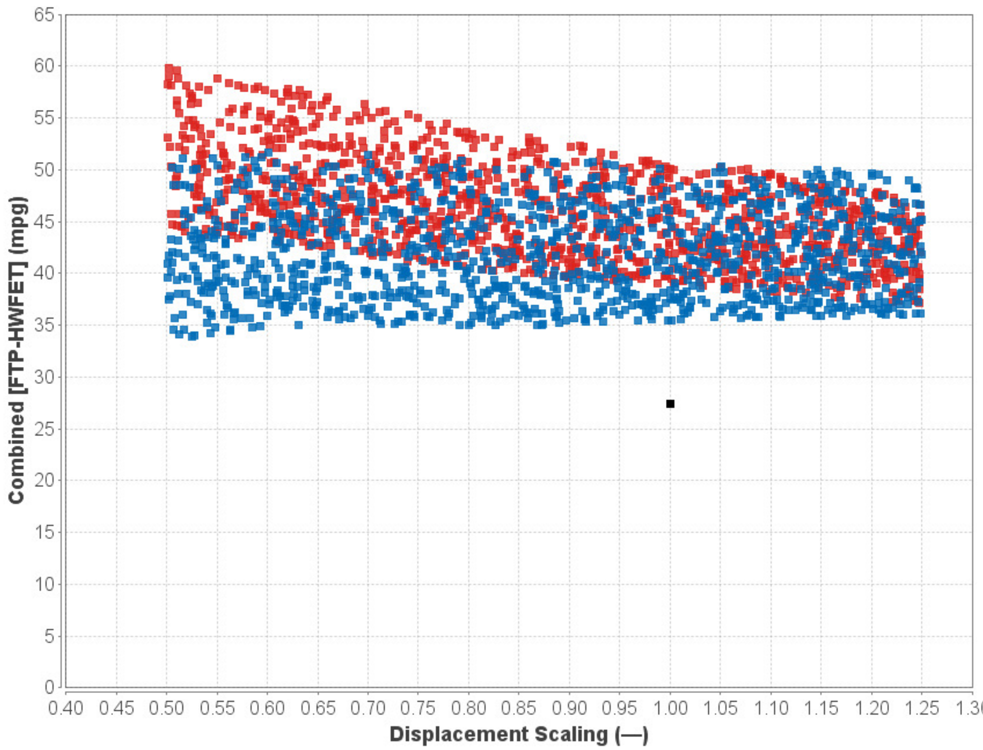

Figure 9.3: Full Size Car Design Space Analysis example. Black point is 2010 baseline; red points are for advanced diesel and dry-clutch DCT; blue points, Stoichiometric DI Turbo with advanced automatic transmission.

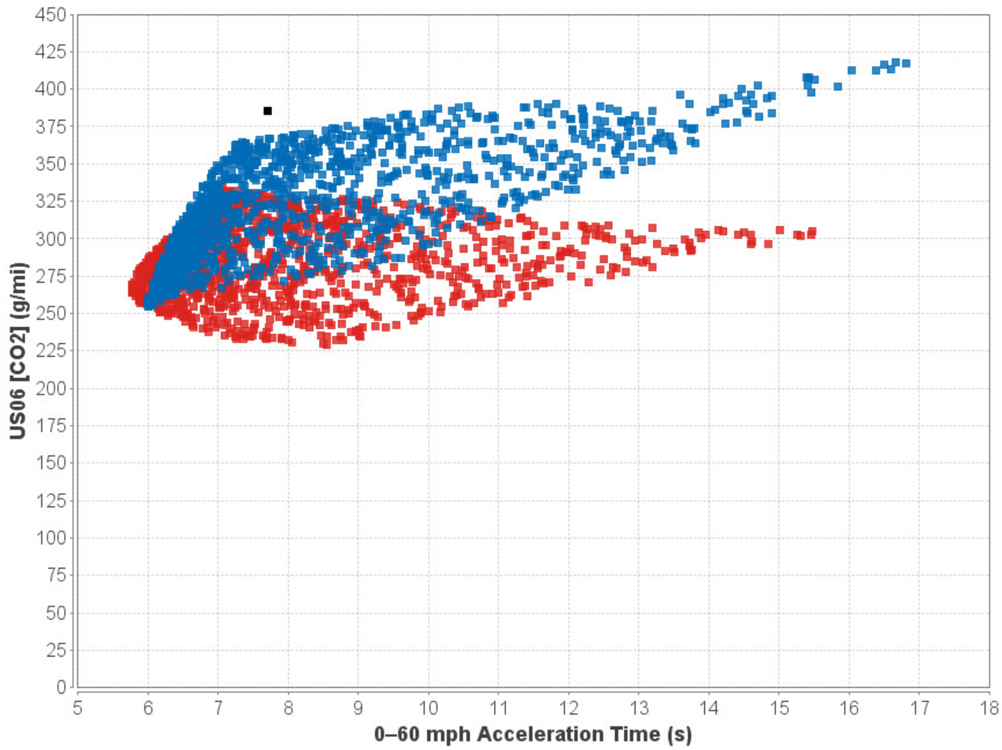

Figure 9.4: Full Size Car Design Space Analysis example. Black point is 2010 baseline; red points are for advanced diesel and dry-clutch DCT; blue points, Stoichiometric DI Turbo with advanced automatic transmission.

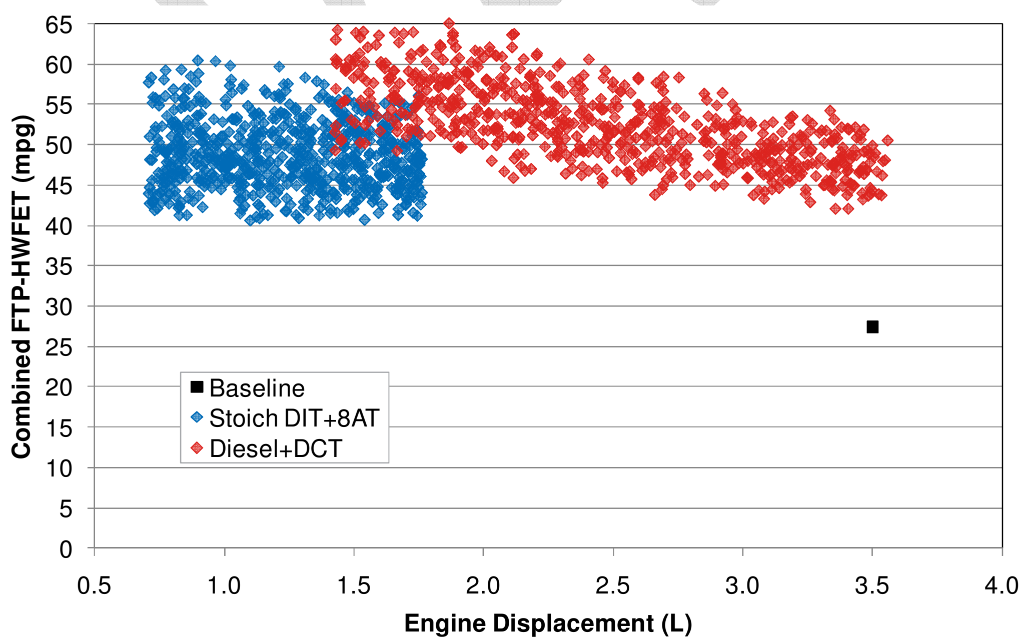

Figure 9.5: Full Size Car Design Space Analysis example. Black point is 2010 baseline; red points are for advanced diesel and dry-clutch DCT; blue points, Stoichiometric DI Turbo with advanced automatic transmission.

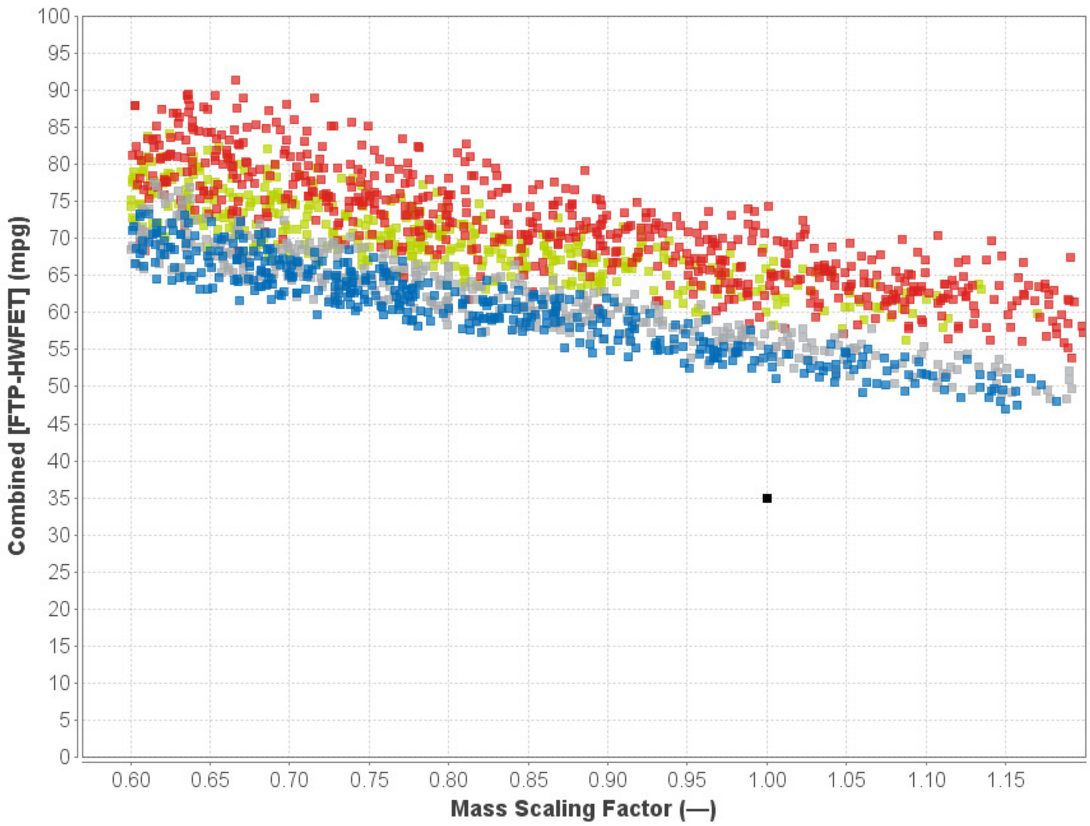

Figure 9.6: Standard Car design space analysis example comparing powertrains with EGR DI Turbo engine. Blue points are with advanced automatic; gray, dry-clutch DCT; green, Powersplit; and red, P2 Hybrid. Black point is 2010 baseline.

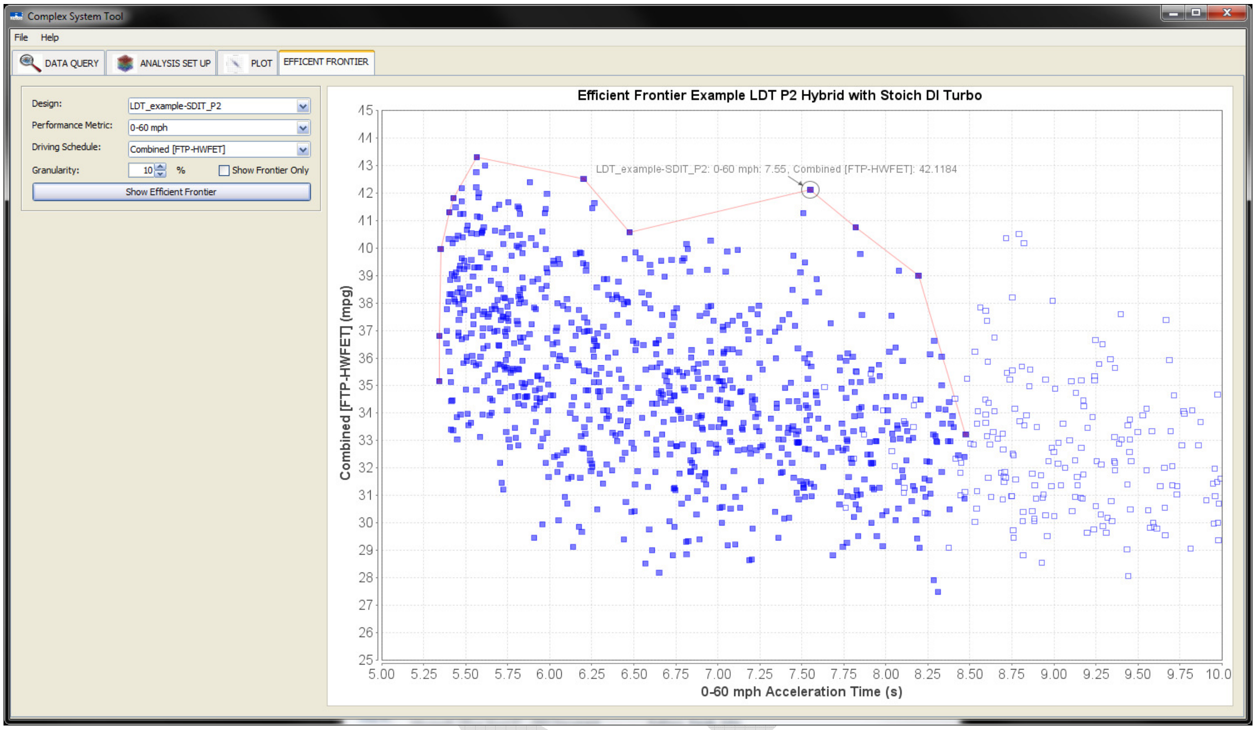

Figure 9.7: Efficient Frontier screen of Data Visualization Tool with example plot.

9.4 Identification and Use of the Efficient Frontier

Part of assessing the selected regions of the design space is to find configurations that balance efficiency and performance. The Data Visualization Tool identifies an Efficient Frontier, which is the bound of the sampled design space that has the most desirable performance. The user must first define a dataset using the Design Space Query, described in Section 9.2, above, and select the Efficient Frontier tab in the Data Visualization Tool. An example of the Efficient Frontier screen is shown in Figure 9.7. The Efficient Frontier is marked out in red. The user can click on the data points along the frontier to discover the vehicle configurations that lie on the frontier.

10. RECOMMENDATIONS FOR FURTHER WORK

Ricardo has the following recommendations for further work on this program:

- More rigorous analysis and simulation of turbo lag effects in the advanced, boosted engines through engine performance simulation tied in with the vehicle models.
- Expansion of the design space to encompass additional drive cycles, such as the NEDC, JC08, or the cold ambient FTP, to understand how the technology packages may apply to other global regions.
- Expansion of the design space to mix 2010 baseline engines and transmissions with the advanced technologies to better understand the relative contributions of engine or transmission technology to the performance of the advanced vehicles.

- Expansion of the design space to include engines with different technology packages, such as a version of the Stoichiometric DI Turbo engine that has a single, fixed cam profile instead of using the CPS valvetrain.
- Expansion of the design space to include additional technologies in one vehicle class to improve understanding of additional technologies.
- Expansion of the design space by sweeping battery capacity.
- Conduct detailed study of simulation results to understand main and interaction effects between technologies.

11. CONCLUSIONS

The following conclusions are supported by this project:

- An independent, objective, and robust analytical study of effectiveness of selected LDV technologies expected to be prevalent in the 2020–2025 timeframe, and their effects on vehicle performance has been completed.

- A comprehensive review process was completed to identify technologies likely to be available in the 2020–2025 timeframe, and to estimate their future performance given current trends and expected developments.

- The vehicle performance models were based upon the underlying physics of the technologies and have been validated with good result to available test data. Quality assurance checks have been made throughout the study to ensure accuracy of the trends in the results.

- The Data Visualization Tool allows EPA and other external stakeholders to examine the design space developed through the program's Complex Systems Modeling approach and to assess trade-offs between various vehicle configurations and their performance. The tool provides the necessary functionality to assess specific vehicle designs or more comprehensively explore the design space.

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APPENDICES

Appendix 1: Abbreviations

AMT	Automated manual transmissions
ARB	California Air Resources Board
BMEP	Brake mean effective pressure
BSFC	Brake specific fuel consumption
CPS	Cam profile switching
CVT	Continuously variable transmission
DCT	Dual clutch transmission
DI	Direct injection
DoE	Design of experiments
DVA	Digital valve actuation
EGR	Exhaust gas recirculation
EPA	United States Environmental Protection Agency
EPAS	Electric power assisted steering
EV	Electric vehicle
FEAD	Front end accessory drive
FIE	Fuel injection equipment
GHG	Greenhouse gas
LHDT	Light heavy-duty truck
ICCT	International Council on Clean Transportation
KERS	Kinetic energy recovery system
LDT	Light-duty truck
LDV	Light-duty vehicle
LEV	Low emissions vehicle
MPV	Multi-purpose vehicle
NO_x	Nitrogen oxides
NVH	Noise, vibration, and harshness
OEM	Original equipment manufacturer
OTAQ	Office of Transportation and Air Quality
PAS	Power assisted steering
PFI	Port fuel injection
PHEV	Plug-in hybrid electric vehicle
PQA	Perrin Quarles Associates
RSM	Response surface model
SCR	Selective catalytic reduction
SI	Spark ignited
SME	Subject matter expert
SOC	State of charge
SULEV	Super ultra low emissions vehicle
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
VA	Valve actuation

Appendix 2: Output Factors for Study

Raw fuel economy in miles per U.S. gallon and GHG emissions in grams of CO_2 per mile over

- FTP75
- HWFET
- US06
- HWFET and FTP combined

Acceleration performance metrics, including

- 0–10 mph acceleration time
- 0–30 mph acceleration time
- 0–50 mph acceleration time
- 0–60 mph acceleration time
- 0–70 mph acceleration time
- 30–50 mph acceleration time
- 50–70 mph acceleration time
- Top speed at 5% grade
- Top speed at 10% grade
- Velocity at 1.3 sec
- Velocity at 3.0 sec
- Distance at 1.3 sec
- Distance at 3.0 sec
- Maximum grade at 70 mph at GCW
- Maximum grade at 60 mph at GCVW (LDT and LHDT only)

Appendix 3: Nominal Runs Results

The table lists the baseline (2010) vehicles first, followed by results by vehicle class. The P2 Hybrids have an electric machine size listed, and all use the DCT. There were no Conventional Stop-Start nominal runs that used the DCT. For the Input Powersplit hybrids, only the traction motor size is listed, as the generator size is a function of the engine and traction motor sizes.

Abbreviations used exclusively in the following table of Nominal Runs Results include the following:

Baseline	The 2010 baseline engine for the given vehicle class
Stoich DIT	Stoichiometric DI Turbo engine
Lean DIT	Lean-Stoichiometric DI Turbo engine
EGR DIT	EGR DI Turbo engine
Adv Diesel	Advanced (2020) diesel
Atk CS	Atkinson cycle engine with CPS
Atk DVA	Atkinson cycle engine with DVA
AT6	Six-speed automatic transmission (baseline or advanced, as appropriate)
AT8	Eight-speed automatic transmission (advanced only)
DCT	Dry or wet clutch DCT, per simulation matrix.
PS	Powersplit planetary gearset

Vehicle Class	Engine Type	Displ (L)	Peak Trq (N.m)	EM Pwr (kW)	Trans-mission	Raw fuel economy (mpg) FTP75	HWFET	US06	Acceleration times (s) 0-10mph	0-30mph	0-50mph	0-60mph	0-70mph	30-50mph	50-70mph	Top Speed (mph) on 5% Grade	10% Grade	Max grade at 60 mph	70 mph	Distance (m) in 1.3 sec	3 sec	Velocity (mph) at 1.3 sec	3 sec
Small Car	Baseline	1.5	145	—	AT6	39.8	48.7	30.3	1.4	4.0	7.4	9.9	13.0	3.4	5.6	94.6	82.2	—	10	2.6	14.7	9.3	22.8
Standard Car	Baseline	2.4	219	—	AT6	30.0	43.5	29.1	1.0	3.1	6.3	8.3	11.4	3.2	5.1	110.4	86.7	—	15	3.9	20.5	14.1	29.5
Full Size Car	Baseline	3.5	335	—	AT6	23.8	33.7	23.6	1.2	3.2	6.1	7.7	9.5	2.9	3.4	127.5	99.6	—	33	3.2	19.3	12.0	29.2
Small MPV	Baseline	2.4	219	—	AT6	27.0	36.1	24.1	1.1	3.4	6.8	9.0	12.6	3.4	5.8	97.9	85.1	—	13	3.3	18.4	12.5	26.9
Large MPV	Baseline	3.8	319	—	AT6	22.0	30.7	21.0	1.1	2.9	6.1	8.6	11.5	3.2	5.4	95.7	82.2	—	16	3.4	20.4	12.9	31.2
LDT	Baseline	5.4	495	—	AT6	16.2	22.6	15.1	1.1	3.1	6.0	8.2	10.8	2.9	4.8	101.4	88.3	20	—	3.4	19.9	12.6	29.8
LHDT	Base SI	6.0	515	—	AT6	11.2	15.1	9.8	1.0	3.1	6.9	9.9	13.3	3.8	6.4	92.8	69.8	15	—	3.7	20.7	14.2	29.9
LHDT	Base Diesel	6.6	895	—	AT6	15.6	19.0	12.3	1.0	3.0	6.7	9.4	13.1	3.7	6.4	99.3	79.3	17	—	4.0	21.3	14.7	30.4
Small Car	Stoich DIT	0.74	157	—	AT6	53.2	55.1	32.4	1.5	4.0	7.4	10.0	13.1	3.4	5.7	96.2	79.3	—	14	2.4	14.1	8.8	22.3
Small Car	Lean DIT	0.74	157	—	AT6	55.1	56.0	32.6	1.5	4.0	7.4	10.0	13.1	3.4	5.7	96.2	79.3	—	14	2.4	14.1	8.8	22.3
Small Car	EGR DIT	0.74	157	—	AT6	55.1	57.4	33.9	1.5	4.0	7.4	10.0	13.1	3.4	5.7	96.2	79.3	—	14	2.4	14.1	8.8	22.3
Small Car	Adv Diesel	1.23	221	—	AT6	55.8	59.4	41.5	1.2	3.7	7.3	9.8	13.2	3.6	5.9	94.0	76.0	—	13	3.2	16.8	10.9	25.1
Small Car	Atk CS	1.66	138	14	DCT6	70.8	59.0	38.1	1.4	3.7	7.5	10.0	13.6	3.8	6.1	85.4	62.1	—	8	2.5	15.5	9.8	24.4
Small Car	Atk DVA	1.66	138	14	DCT6	71.7	60.5	39.4	1.4	3.7	7.5	10.0	13.6	3.8	6.1	85.4	62.1	—	8	2.5	15.5	9.8	24.4
Small Car	Stoich DIT	0.59	124	14	DCT6	68.2	57.3	37.0	1.4	3.8	7.2	9.6	12.6	3.4	5.4	87.5	70.7	—	10	2.4	15.1	9.4	23.6
Small Car	Lean DIT	0.59	124	14	DCT6	68.4	57.7	37.3	1.4	3.8	7.2	9.6	12.6	3.4	5.4	87.5	70.7	—	10	2.4	15.1	9.4	23.6
Small Car	EGR DIT	0.59	124	14	DCT6	70.2	59.9	39.0	1.4	3.8	7.2	9.6	12.6	3.4	5.4	87.5	70.7	—	10	2.4	15.1	9.4	23.6
Small Car	Atk CS	1.66	138	40	PS	64.2	59.5	38.0	1.8	4.7	7.9	9.8	12.2	3.2	4.3	93.5	77.4	—	8	1.5	11.1	6.7	18.5
Small Car	Atk DVA	1.66	138	40	PS	67.3	60.0	39.0	1.8	4.7	7.9	9.8	12.1	3.2	4.2	93.5	77.9	—	8	1.5	11.1	6.7	18.5
Small Car	Stoich DIT	0.59	124	40	PS	64.7	57.2	35.2	1.9	4.8	8.2	10.4	13.1	3.4	4.9	89.5	71.3	—	8	1.5	10.8	6.5	18.1
Small Car	Lean DIT	0.59	124	40	PS	65.8	57.4	35.2	1.9	4.8	8.2	10.4	13.1	3.4	4.9	89.1	71.3	—	8	1.5	10.8	6.5	18.1
Small Car	EGR DIT	0.59	124	40	PS	67.7	60.1	36.7	1.9	4.8	8.2	10.4	13.1	3.4	4.9	89.1	71.3	—	8	1.5	10.8	6.5	18.1
Standard Car	Stoich DIT	1.04	220	—	AT8	44.8	54.5	32.5	1.0	3.1	6.2	8.5	11.4	3.1	5.2	107.7	86.2	—	15	3.7	20.7	14.0	29.7
Standard Car	Lean DIT	1.04	220	—	AT8	46.6	55.5	32.8	1.0	3.1	6.2	8.5	11.4	3.1	5.2	107.7	86.2	—	15	3.7	20.7	14.0	29.7
Standard Car	EGR DIT	1.04	220	—	AT8	46.4	56.7	34.0	1.0	3.1	6.2	8.5	11.4	3.1	5.2	107.7	86.2	—	15	3.7	20.7	14.0	29.7
Standard Car	Atk CS	2.40	200	24	DCT8	64.6	59.7	39.8	1.2	3.4	6.5	8.6	11.4	3.1	4.9	101.3	78.4	—	11	2.8	17.4	11.0	27.3
Standard Car	Atk DVA	2.40	200	24	DCT8	65.9	61.0	40.5	1.2	3.4	6.5	8.6	11.4	3.1	4.9	101.3	78.4	—	11	2.8	17.4	11.0	27.3
Standard Car	Stoich DIT	0.83	176	24	DCT8	61.9	57.2	36.9	1.3	3.6	6.5	8.6	11.3	2.9	4.8	98.1	77.4	—	12	2.6	16.6	10.5	25.8
Standard Car	Lean DIT	0.83	176	24	DCT8	62.9	58.0	36.7	1.3	3.6	6.5	8.6	11.3	2.9	4.8	98.1	77.4	—	12	2.6	16.6	10.5	25.8
Standard Car	EGR DIT	0.83	176	24	DCT8	65.1	59.7	38.4	1.3	3.6	6.5	8.6	11.3	2.9	4.8	98.1	77.4	—	12	2.6	16.6	10.5	25.8
Standard Car	Atk CS	2.40	200	80	PS	53.3	51.7	36.8	1.4	3.6	6.2	8.0	10.2	2.6	4.0	105.2	85.5	—	10	2.2	15.2	9.3	25.1
Standard Car	Atk DVA	2.40	200	80	PS	56.4	53.3	37.6	1.4	3.6	6.2	8.0	10.2	2.6	4.0	105.2	85.8	—	10	2.2	15.2	9.3	25.1
Standard Car	Stoich DIT	0.83	176	80	PS	55.6	51.7	35.4	1.5	3.7	6.6	8.7	11.3	2.9	4.7	99.0	78.1	—	10	2.1	14.9	9.1	24.4
Standard Car	Lean DIT	0.83	176	80	PS	57.9	53.5	36.0	1.5	3.7	6.6	8.7	11.3	2.9	4.7	99.0	78.1	—	10	2.1	14.9	9.1	24.4
Standard Car	EGR DIT	0.83	176	80	PS	58.0	54.8	37.1	1.5	3.7	6.6	8.7	11.3	2.9	4.7	99.0	78.1	—	10	2.1	14.9	9.1	24.4
Small MPV	Stoich DIT	1.13	239	—	AT8	38.8	42.6	25.7	1.2	3.3	6.5	8.9	12.0	3.2	5.5	99.8	81.2	—	14	3.1	18.7	11.6	28.3
Small MPV	Lean DIT	1.13	239	—	AT8	40.3	43.1	25.9	1.2	3.3	6.5	8.9	12.0	3.2	5.5	99.8	81.2	—	14	3.1	18.7	11.6	28.3
Small MPV	EGR DIT	1.13	239	—	AT8	40.3	44.4	27.0	1.2	3.3	6.5	8.9	12.0	3.2	5.5	99.8	81.2	—	14	3.1	18.7	11.6	28.3
Small MPV	Atk CS	2.60	217	20	DCT8	52.9	45.5	29.6	1.4	3.7	7.1	9.3	12.6	3.4	5.5	91.3	76.7	—	10	2.3	15.4	9.4	25.1
Small MPV	Atk DVA	2.60	217	20	DCT8	54.1	46.8	30.3	1.4	3.7	7.1	9.3	12.6	3.4	5.5	91.3	76.7	—	10	2.3	15.4	9.5	25.1
Small MPV	Stoich DIT	0.90	190	20	DCT8	50.1	44.2	28.5	1.5	3.9	7.0	9.4	12.3	3.1	5.3	90.6	72.7	—	11	2.1	14.6	8.9	23.7
Small MPV	Lean DIT	0.90	190	20	DCT8	50.8	44.5	28.5	1.5	3.9	7.0	9.4	12.3	3.1	5.3	90.6	72.7	—	11	2.1	14.6	8.9	23.7
Small MPV	EGR DIT	0.90	190	20	DCT8	52.0	46.1	29.8	1.5	3.9	7.0	9.4	12.3	3.1	5.3	90.6	72.7	—	11	2.1	14.6	8.9	23.7
Small MPV	Atk CS	2.60	217	70	PS	44.3	39.6	25.1	1.9	4.6	7.4	9.1	11.1	2.8	3.7	98.3	81.4	—	9	1.4	10.5	6.1	18.0
Small MPV	Atk DVA	2.60	217	70	PS	49.3	42.3	28.6	1.9	4.6	7.4	9.1	11.1	2.8	3.7	98.3	81.6	—	9	1.4	10.5	6.1	18.0
Small MPV	Stoich DIT	0.90	190	70	PS	49.1	42.2	27.4	1.9	4.7	8.0	10.3	13.1	3.3	5.1	92.2	73.3	—	8	1.4	10.4	6.1	17.7
Small MPV	Lean DIT	0.90	190	70	PS	50.8	42.7	27.3	1.9	4.7	8.0	10.3	13.2	3.3	5.2	92.2	73.3	—	8	1.4	10.4	6.1	17.7
Small MPV	EGR DIT	0.90	190	70	PS	51.3	44.9	28.8	1.9	4.7	8.0	10.3	13.2	3.3	5.2	92.2	73.3	—	8	1.4	10.4	6.1	17.7

Vehicle Class	Engine Type	Displ (L)	Peak Trq (N.m)	EM Pwr (kW)	Trans-mission	Raw fuel economy (mpg) FTP75	HWFET	US06	Acceleration times (s) 0-10mph	0-30mph	0-50mph	0-60mph	0-70mph	30-50mph	50-70mph	Top Speed (mph) on 5% Grade	10% Grade	Max grade at 60 mph	70 mph	Distance (m) in 1.3 sec	3 sec	Velocity (mph) at 1.3 sec	3 sec
Full Size Car	Stoich DIT	1.41	298	—	AT8	37.1	43.2	27.2	1.2	3.0	5.7	7.4	9.8	2.7	4.1	116.1	95.8	—	20	3.2	19.7	12.1	30.7
Full Size Car	Lean DIT	1.41	298	—	AT8	38.8	44.0	27.6	1.2	3.0	5.7	7.4	9.8	2.7	4.1	116.1	95.8	—	20	3.2	19.7	12.1	30.7
Full Size Car	EGR DIT	1.41	298	—	AT8	38.6	44.9	28.5	1.2	3.0	5.7	7.4	9.8	2.7	4.1	116.1	95.8	—	20	3.2	19.7	12.1	30.7
Full Size Car	Adv Diesel	2.85	503	—	AT8	38.2	46.5	32.5	1.1	2.9	5.6	7.5	9.8	2.7	4.2	113.7	94.9	—	19	3.5	20.2	12.4	31.1
Full Size Car	Atk CS	3.80	317	28	DCT8	49.9	46.2	31.5	1.2	3.0	5.5	7.1	9.0	2.5	3.5	113.4	87.9	—	22	2.8	18.6	11.4	30.1
Full Size Car	Atk DVA	3.80	317	28	DCT8	51.1	47.4	31.9	1.2	3.0	5.5	7.1	9.0	2.5	3.5	113.4	87.9	—	22	2.8	18.6	11.4	30.1
Full Size Car	Stoich DIT	1.13	238	28	DCT8	49.8	46.5	31.3	1.3	3.4	6.1	7.7	10.0	2.7	3.9	105.9	86.6	—	15	2.5	16.9	10.5	27.1
Full Size Car	Lean DIT	1.13	238	28	DCT8	50.4	46.8	31.4	1.3	3.4	6.1	7.7	10.0	2.7	3.9	105.9	86.6	—	15	2.5	16.9	10.5	27.1
Full Size Car	EGR DIT	1.13	238	28	DCT8	51.7	48.3	32.6	1.3	3.4	6.1	7.7	10.0	2.7	3.9	105.9	86.6	—	15	2.5	16.9	10.5	27.1
Full Size Car	Atk CS	3.80	317	120	PS	40.3	38.7	29.2	1.3	3.2	5.6	7.1	8.7	2.4	3.1	119.2	103.5	—	16	2.7	17.7	10.7	28.6
Full Size Car	Atk DVA	3.80	317	120	PS	43.0	40.8	29.8	1.3	3.2	5.6	7.1	8.7	2.4	3.1	119.2	103.5	—	16	2.7	17.7	10.7	28.7
Full Size Car	Stoich DIT	1.13	238	120	PS	46.6	42.0	29.8	1.3	3.2	6.0	7.8	10.0	2.8	4.0	106.2	87.6	—	12	2.6	17.2	10.4	28.2
Full Size Car	Lean DIT	1.13	238	120	PS	48.0	41.8	29.9	1.3	3.2	5.9	7.8	10.0	2.7	4.1	106.2	87.7	—	12	2.6	17.2	10.4	28.3
Full Size Car	EGR DIT	1.13	238	120	PS	47.9	43.6	31.1	1.3	3.2	6.0	7.8	10.0	2.8	4.0	106.2	87.7	—	12	2.6	17.2	10.4	28.2
Large MPV	Stoich DIT	1.31	277	—	AT8	34.8	39.2	23.7	1.1	3.2	6.4	8.6	11.5	3.2	5.1	103.7	84.5	—	15	3.4	19.8	13.2	29.1
Large MPV	Lean DIT	1.31	277	—	AT8	36.0	39.8	23.9	1.1	3.2	6.4	8.6	11.5	3.2	5.1	103.7	84.5	—	15	3.4	19.8	13.2	29.1
Large MPV	EGR DIT	1.31	277	—	AT8	36.2	40.9	24.9	1.1	3.2	6.4	8.6	11.5	3.2	5.1	103.7	84.5	—	15	3.4	19.8	13.2	29.1
Large MPV	Adv Diesel	2.61	460	—	AT8	37.3	43.3	29.4	1.1	3.0	6.2	8.6	11.5	3.2	5.3	101.9	83.9	—	14	3.7	20.9	13.3	30.5
Large MPV	Atk CS	3.15	263	25	DCT8	48.3	42.4	27.5	1.4	3.6	6.7	8.8	11.6	3.1	4.9	95.5	82.3	—	11	2.4	15.7	9.7	26.0
Large MPV	Atk DVA	3.15	263	25	DCT8	48.8	43.5	27.7	1.4	3.6	6.7	8.8	11.6	3.1	4.9	95.5	82.3	—	11	2.4	15.7	9.7	26.0
Large MPV	Stoich DIT	1.05	221	25	DCT8	47.7	42.2	26.2	1.5	3.8	6.9	9.1	11.9	3.1	5.0	94.3	75.6	—	12	2.2	14.7	9.0	23.9
Large MPV	Lean DIT	1.05	221	25	DCT8	47.4	42.6	26.8	1.5	3.8	6.9	9.1	11.9	3.1	5.0	94.3	75.6	—	12	2.2	14.7	9.0	23.9
Large MPV	EGR DIT	1.05	221	25	DCT8	47.6	43.0	27.6	1.5	3.8	6.9	9.1	11.9	3.1	5.0	94.3	75.6	—	12	2.2	14.7	9.0	23.9
Large MPV	Atk CS	3.15	263	90	PS	41.7	38.6	26.5	1.8	4.2	7.0	8.8	11.1	2.8	4.1	103.4	86.0	—	11	1.5	11.7	6.8	20.2
Large MPV	Atk DVA	3.15	263	90	PS	44.3	39.6	27.0	1.8	4.2	7.0	8.8	11.1	2.8	4.1	103.4	86.5	—	11	1.5	11.7	6.8	20.2
Large MPV	Stoich DIT	1.05	221	90	PS	44.8	39.3	25.8	1.8	4.3	7.5	9.7	12.5	3.2	5.0	100.2	76.5	—	9	1.5	11.5	6.7	19.7
Large MPV	Lean DIT	1.05	221	90	PS	45.7	40.6	25.7	1.8	4.3	7.5	9.7	12.5	3.2	5.0	100.8	76.5	—	9	1.5	11.5	6.7	19.7
Large MPV	EGR DIT	1.05	221	90	PS	47.0	41.5	27.3	1.8	4.3	7.5	9.7	12.5	3.2	5.0	100.8	76.5	—	9	1.5	11.5	6.7	19.7
LDT	Stoich DIT	1.94	410	—	AT8	23.8	26.6	16.3	1.1	3.0	6.0	8.1	10.8	3.0	4.8	105.6	86.9	21	—	3.4	20.5	13.2	30.5
LDT	Lean DIT	1.94	410	—	AT8	24.6	27.0	16.4	1.1	3.0	6.0	8.1	10.8	3.0	4.8	105.6	86.9	21	—	3.4	20.5	13.2	30.5
LDT	EGR DIT	1.94	410	—	AT8	24.8	27.7	17.1	1.1	3.0	6.0	8.1	10.8	3.0	4.8	105.6	86.9	21	—	3.4	20.5	13.2	30.5
LDT	Adv Diesel	4.28	694	—	AT8	26.4	30.4	20.5	1.0	2.9	5.8	8.0	10.6	2.9	4.8	104.6	87.2	20	—	3.7	21.4	13.5	31.5
LDT	Atk CS	4.60	384	50	DCT8	33.2	29.0	19.4	1.1	3.1	5.9	7.8	10.3	2.8	4.4	95.6	83.8	17	—	3.1	19.1	12.2	29.5
LDT	Atk DVA	4.60	384	50	DCT8	33.9	29.7	19.7	1.1	3.1	5.9	7.8	10.3	2.8	4.4	95.6	83.8	17	—	3.1	19.1	12.2	29.5
LDT	Stoich DIT	1.55	327	50	DCT8	32.5	28.4	18.9	1.2	3.3	6.1	7.9	10.4	2.8	4.3	96.1	78.0	16	—	3.0	18.2	11.7	27.9
LDT	Lean DIT	1.55	327	50	DCT8	33.0	28.6	18.8	1.2	3.3	6.1	7.9	10.4	2.8	4.3	96.1	78.0	16	—	3.0	18.2	11.7	27.9
LDT	EGR DIT	1.55	327	50	DCT8	33.8	29.6	19.7	1.2	3.3	6.1	7.9	10.4	2.8	4.3	96.1	78.0	16	—	3.0	18.2	11.7	27.9
LHDT	Stoich DIT	2.30	486	—	AT8	16.5	18.3	11.1	1.0	3.2	7.0	9.8	13.4	3.8	6.4	95.1	74.8	16	—	3.6	20.2	13.9	28.6
LHDT	Lean DIT	2.30	486	—	AT8	16.8	18.4	11.2	1.0	3.2	7.0	9.8	13.4	3.8	6.4	95.1	74.8	16	—	3.6	20.2	13.9	28.6
LHDT	EGR DIT	2.30	486	—	AT8	17.2	19.1	11.7	1.0	3.2	7.0	9.8	13.4	3.8	6.4	95.1	74.8	16	—	3.6	20.2	13.9	28.6
LHDT	Adv Diesel	6.60	895	—	AT8	19.8	21.5	14.1	0.9	2.9	6.3	8.8	11.8	3.4	5.5	101.5	79.3	17	—	4.2	22.2	15.1	31.0

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