Project Report

Project Title: **Heavy-Duty Engine Valvetrain Technology Cost Assessment**

FEV Project Number: **P314406-01**

This project report has been reviewed and complies with the quality assurance procedures of FEV North America, Inc. The project report is adequate for delivery to the customer.

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Heavy-Duty Engine Valvetrain Technology Cost Assessment

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Disclaimer

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EXECUTIVE SUMMARY

The United States Environmental Protection Agency (EPA) contracted with FEV North America Inc. to determine Net Incremental Total Manufacturing Cost (NITMC) for various Valvetrain technologies in heavy and medium duty engines. Specific technologies under consideration are Eaton's Cylinder Deactivation system and Mechadyne's FlexValve system.

In contrast to comparable cost analyses done in the past[1 2], which rely heavily on supplier price quotes for key components, this study is based to a large degree on teardowns of vehicle systems that employ the new technologies, and of similar systems without the new technologies. For technologies that are not yet in production, part drawings and CAD data were utilized to develop cost estimates. Analysts with expertise in automotive design, materials, and manufacturing then compare the components and evaluate the differences. Using databases for materials, labor, manufacturing overhead, and mark-up costs, the overall cost to manufacture individual parts are calculated and summed into final results. A model consisting of an extensive set of linked spreadsheets and associated macros has been developed to perform the calculations, to track the input data, identify sources of information, describe assumptions used in the case study, and provide analysis tools (such as forecasting to future years).

This report describes the cost assessment conducted on Cummins X15 engine valvetrain, which acts as a baseline for evaluating a Cylinder Deactivation system and a FlexValve system, respectively. **Figure 0-1** shows the valvetrain modules considered for this study. For the rest of the modules such as valves, cover, spring, retainers, cotter & seats, harness (specific to valvetrain components) past benchmarking studies were used to develop a complete Valvetrain system cost. The Cummins X15 valvetrain employs a feed-through camshaft design which is not typical for new SOHC engines.

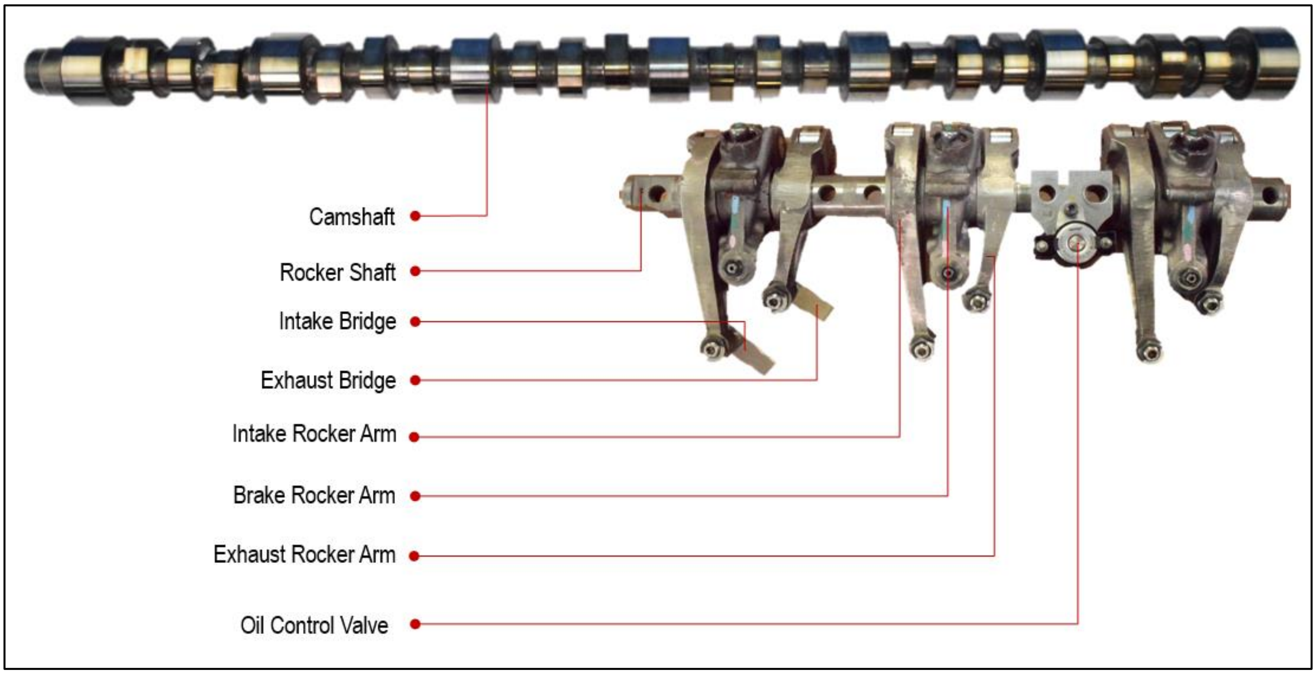


Figure 0-1: Valvetrain Components Considered for this Study

The project was divided into four subtasks:

1. Cost assessment of the Baseline Cummins X15 valvetrain components considering boundary conditions pertaining to cross-platform sharing capability for each component
2. Cost assessment of Eaton's Cylinder Deactivation module and evaluating key design and manufacturing attributes compared to Baseline system
3. Cost assessment of Mechadyne's FlexValve module and evaluating key design and manufacturing attributes compared to Baseline system
4. Extending the study to the other engine variants like Cummins L9 engine, which has a type V valvetrain configuration (pushrod) and other SOHC engines that have a directly supported camshaft

The complete cost assessment of the Cummins X15 engine valvetrain is shown in **Table 0-1**. The calculated costs are referred to as Total Manufacturing Costs (TMC) inclusive of supplier direct and indirect manufacturing costs and OEM direct manufacturing costs. Direct manufacturing costs include material, labor and manufacturing overhead whereas indirect manufacturing costs include end-item scrap allowance, selling, general and administrative expenses (SG&A), profit, and engineering, design and testing expenses (ED&T). Cost to assembly valvetrain modules to the rest of the engine is included in OEM direct manufacturing cost.

Table 0-1: Cummins X15 Valvetrain Cost Breakdown

Subsystem	Sub-subsystem / Module	QTY	Unit Mass	Total Mass	Mass Total Percent "%"	Unit Cost	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain			kg	kg	%	US $	US $	%
01	Exhaust Bridge Module	6	0.147	0.884	1.52%	2.49	14.94	2.16%
02	Intake Bridge Module	6	0.145	0.869	1.50%	1.44	8.66	1.25%
03	Exhaust Rocker Arm Module	6	0.711	4.267	7.35%	11.46	68.77	9.94%
04	Brake Rocker Arm Module	6	1.285	7.711	13.28%	15.24	91.41	13.22%
05	Intake Rocker Arm Module	6	0.982	5.892	10.15%	11.89	71.33	10.31%
06	Oil Control Module	2	0.532	1.064	1.83%	10.38	20.77	3.00%
07	Rocker Shaft	2	3.022	6.044	10.41%	32.48	64.96	9.39%
08	Cam Shaft Module	1	21.100	21.100	36.35%	144.86	144.86	20.94%
09	Other Valvetrain Modules			10.222	17.61%		184.57	26.69%
10	Assembly			0.000	0.00%		21.36	3.09%
Total Cost				58.05	100%		691.62	100%
Cost per cylinder = $115.27								

Table 0-2 provides the TMC for 15L Engine valvetrain with Cylinder Deactivation system installed on all 6 cylinders. Oil Control Module includes 4 OCV mounting modules installed between the cylinders on the rocker shaft, 6 OCVs (oil control valve) for CDA and 2 OCVs for engine compression braking.

Table 0-2: 15L Engine Valvetrain w/ CDA Cost Breakdown

Subsystem	Sub-subsystem / Module	QTY	Unit Mass	Total Mass	Mass Total Percent "%"	Unit Cost	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain			kg	kg	%	US $	US $	%
01	Exhaust Bridge Module	6	0.263	1.580	2.42%	4.29	25.76	2.84%
02	Intake Bridge Module	6	0.120	0.722	1.10%	1.39	8.36	0.92%
03	Exhaust Rocker Arm Module	6	1.145	6.870	10.51%	20.02	120.14	13.26%
04	Brake Rocker Arm Module	6	0.903	5.416	8.28%	13.40	80.43	8.88%
05	Intake Rocker Arm Module	6	1.315	7.892	12.07%	21.42	128.51	14.18%
06	Oil Control Module			5.296	8.10%		112.87	12.46%
07	Rocker Shaft	2	3.022	6.044	9.24%	35.09	70.18	7.74%
08	Cam Shaft	1	21.100	21.100	32.27%	144.86	144.86	15.99%
09	Other Valvetrain Modules			10.472	16.01%		189.96	20.96%
10	Assembly			0.000	0.00%		25.13	2.77%
Total Cost				65.39	100%		906.20	100%
Cost per cylinder = $151.03								

Table 0-3 provides the TMC for 15L Engine valvetrain with FlexValve system to implement late intake valve closing (LIVC) via continuously variable intake valve lift. Intake rocker arm and Camshaft module in baseline are replaced with FlexValve rockers and FlexValve camshaft to achieve LIVC. Cost assessment shown below is applicable only for a feed-through camshaft design which requires additional cam bearing elements included as part of the Camshaft.

Table 0-3: 15L Engine Valvetrain w/ LIVC Cost Breakdown

Subsystem	Sub-subsystem / Module	QTY	Unit Mass	Total Mass	Mass Total Percent "%"	Unit Cost	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain			kg	kg	%	US $	US $	%
01	Exhaust Bridge Module	6	0.174	1.046	1.47%	2.57	15.42	1.60%
02	Intake Bridge Module	6	0.145	0.869	1.22%	1.44	8.66	0.90%
03	Exhaust Rocker Arm Module	6	0.865	5.191	7.29%	11.95	71.69	7.43%
04	Brake Rocker Arm Module	6	1.285	7.711	10.83%	15.24	91.41	9.48%
05	Intake Rocker Arm Module	6	2.122	12.733	17.89%	26.81	160.88	16.68%
06	Oil Control Module	2	0.532	1.064	1.50%	10.38	20.77	2.15%
07	Rocker Shaft	1	6.044	6.044	8.49%	68.52	68.52	7.10%
08	Cam Shaft	1	26.285	26.285	36.94%	319.30	319.30	33.10%
09	Other Valvetrain Modules			10.222	14.36%		184.57	19.13%
10	Assembly			0.000	0.00%		23.51	2.44%
Total Cost				71.16	100%		964.74	100%
Cost per cylinder = $160.79								

Based on the figures provided above, the Net Incremental Total Manufacturing Cost (NITMC) to install Cylinder Deactivation system in all 6 cylinders of the Baseline valvetrain is $214.58 and NITMC to install FlexValve rockers and camshaft is $273.12. **Table 0-4** and **Figure 0-2** show the cost difference in each of the Valvetrain modules evaluated.

Table 0-4: 15L Engine Type III Valvetrain Baseline vs CDA vs LIVC – Cost Comparison (feed-through camshaft design)

Cost Comparison (15 Engine Valvetrain) (Baseline vs CDA & Baseline vs LIVC)							
ID	Module	Baseline	CDA	Delta	Baseline	LIVC	Delta
1	Exhaust Bridge Module	$14.94	$25.76	($10.83)	$14.94	$15.42	($0.49)
2	Intake Bridge Module	$8.66	$8.36	$0.30	$8.66	$8.66	
3	Exhaust Rocker Arm Module	$68.77	$120.14	($51.37)	$68.77	$71.69	($2.92)
4	Brake Rocker Arm Module	$91.41	$80.43	$10.99	$91.41	$91.41	
5	Intake Rocker Arm Module	$71.33	$128.51	($57.18)	$71.33	$160.88	($89.56)
6	Oil Control Module	$20.77	$112.87	($92.10)	$20.77	$20.77	
7	Rocker Shaft	$64.96	$70.18	($5.23)	$64.96	$68.52	($3.57)
8	Cam Shaft	$144.86	$144.86		$144.86	$319.30	($174.44)
9	Intake Valve	$34.91	$34.91		$34.91	$34.91	
	Exhaust Valve	$39.81	$39.81		$39.81	$39.81	
	Valve cover	$54.48	$54.48		$54.48	$54.48	
	Valve spring	$38.74	$38.74		$38.74	$38.74	
	Retainers, Cotters, Seats	$15.06	$15.06		$15.06	$15.06	
	Harness	$1.57	$6.96	($5.39)	$1.57	$1.57	
10	Assembly of all Components	$21.36	$25.13	($3.77)	$21.36	$23.51	($2.15)
Total		$691.62	$906.20	($214.58)	$691.62	$964.74	($273.12)

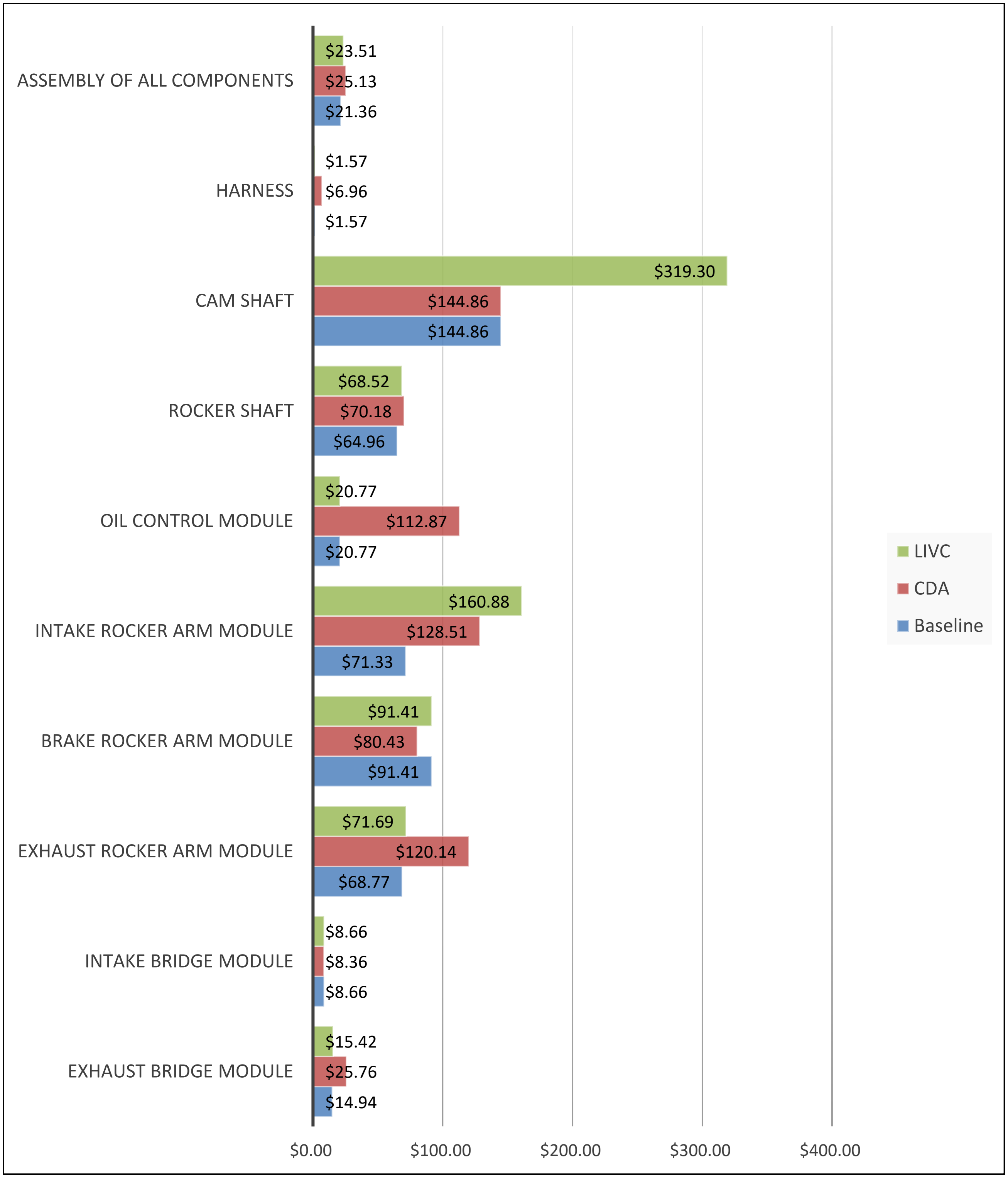


Figure 0-2: Type III Engine Valvetrain Technologies Cost comparison (feed-through camshaft design)

The FlexValve camshaft fits into the same package as the original solid camshaft but requires shrunk bearings to help support camshaft in the cylinder head. Engines like Volvo D13, Ford Ecotorq and

MAN D2676 (International) have SOHC valvetrain with split bearing caps that would not require additional bearing journal components for the FlexValve assembled camshaft. **Table 0-5** and **Figure 0-3** shows NITMC for a SOHC engine where camshaft is directly supported in the tube eliminating the need for bearings and additional machining for clearance to FlexValve rockers and rocker shaft.

Table 0-5 provides the TMC for 15L Engine valvetrain with FlexValve system and directly supported camshaft.

Table 0-5: 15L Engine Valvetrain w/ LIVC Cost Breakdown (Directly supported camshaft)

Subsystem	Sub-subsystem / Module	QTY	Unit Mass	Total Mass	Mass Total Percent "%"	Unit Cost	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain			kg	kg	%	US $	US $	%
01	Exhaust Bridge Module	6	0.174	1.046	1.57%	2.57	15.42	1.71%
02	Intake Bridge Module	6	0.145	0.869	1.30%	1.44	8.66	0.96%
03	Exhaust Rocker Arm Module	6	0.865	5.191	7.77%	12.32	73.95	8.19%
04	Brake Rocker Arm Module	6	1.285	7.711	11.54%	15.13	90.78	10.06%
05	Intake Rocker Arm Module	6	2.122	12.733	19.06%	26.81	160.88	17.83%
06	Oil Control Module	2	0.532	1.064	1.59%	10.38	20.77	2.30%
07	Rocker Shaft	1	6.044	6.044	9.05%	64.96	64.96	7.20%
08	Cam Shaft	1	21.934	21.934	32.83%	258.91	258.91	28.69%
09	Other Valvetrain Modules			10.222	15.30%		184.57	20.45%
10	Assembly			0.000	0.00%		23.51	2.61%
	Total Cost			66.81	100%		902.41	100%
	Cost per cylinder = $150.4							

As shown in **Table 0-6**, NITMC to install Cylinder Deactivation system in all 6 cylinders of the Baseline valvetrain (with directly supported camshaft) is $214.58 and NITMC to install FlexValve rockers and camshaft is $213.26.

Table 0-6: 15L Engine Type III Valvetrain Baseline vs CDA vs LIVC – Cost Comparison (directly supported camshaft design)

Cost Comparison (15 Engine Valvetrain) (Baseline vs CDA & Baseline vs LIVC)							
ID	Module	Baseline	CDA	Delta	Baseline	LIVC	Delta
1	Exhaust Bridge Module	$14.94	$25.76	($10.83)	$14.94	$15.42	($0.49)
2	Intake Bridge Module	$8.66	$8.36	$0.30	$8.66	$8.66	
3	Exhaust Rocker Arm Module	$68.77	$120.14	($51.37)	$69.49	$73.95	($4.46)
4	Brake Rocker Arm Module	$91.41	$80.43	$10.99	$89.75	$90.78	($1.03)
5	Intake Rocker Arm Module	$71.33	$128.51	($57.18)	$69.80	$160.88	($91.08)
6	Oil Control Module	$20.77	$112.87	($92.10)	$20.77	$20.77	
7	Rocker Shaft	$64.96	$70.18	($5.23)	$64.96	$64.96	
8	Cam Shaft	$144.86	$144.86		$144.86	$258.91	($114.05)

9	Intake Valve	$34.91	$34.91		$34.91	$34.91	
	Exhaust Valve	$39.81	$39.81		$39.81	$39.81	
	Valve cover	$54.48	$54.48		$54.48	$54.48	
	Valve spring	$38.74	$38.74		$38.74	$38.74	
	Retainers, Cotters, Seats	$15.06	$15.06		$15.06	$15.06	
	Harness	$1.57	$6.96	($5.39)	$1.57	$1.57	
10	Assembly of all Components	$21.36	$25.13	($3.77)	$21.36	$23.51	($2.15)
Total		**$691.62**	**$906.20**	**($214.58)**	**$689.15**	**$902.41**	**($213.26)**

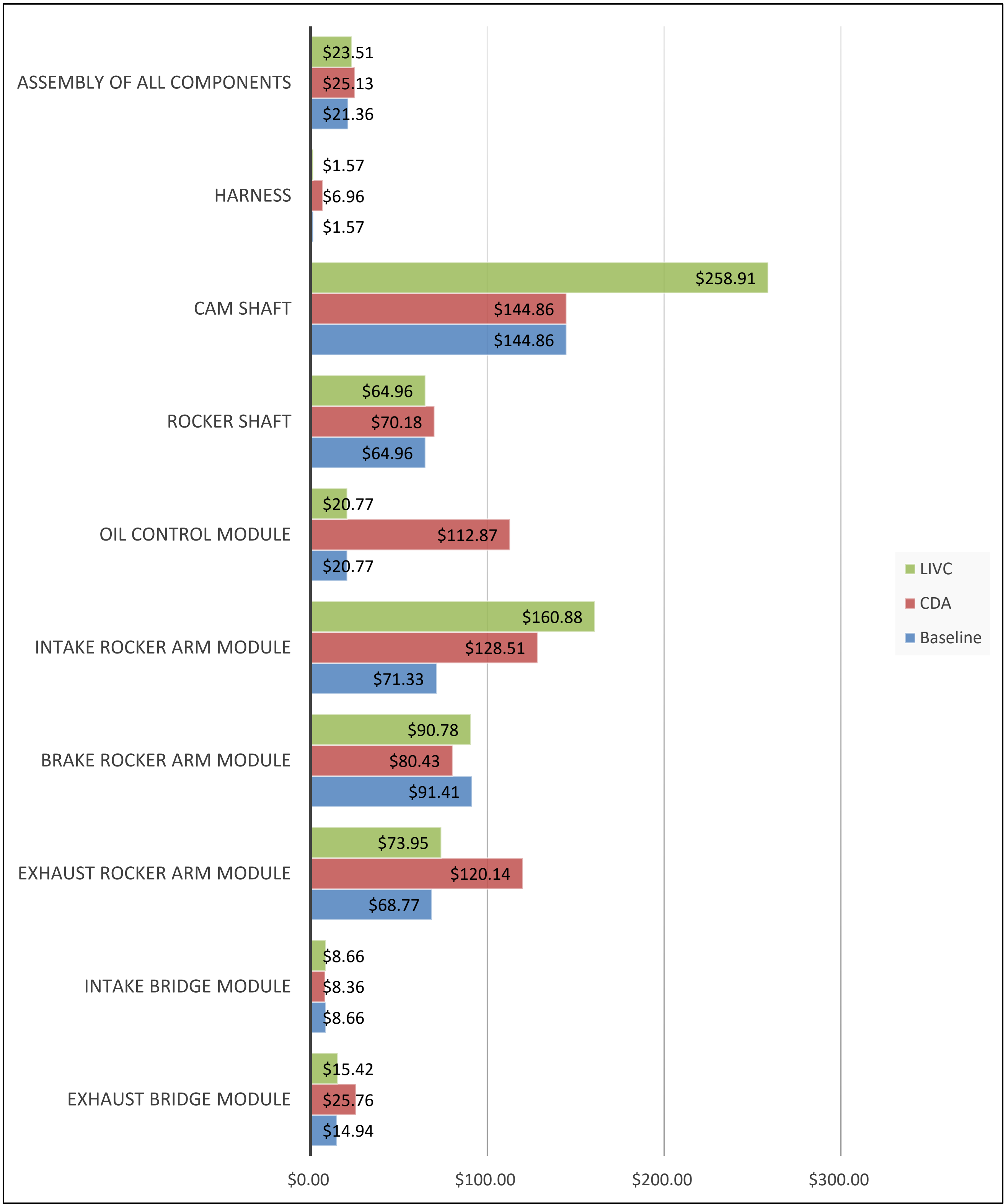


Figure 0-3: 15L Engine Type III Valvetrain Baseline vs CDA vs LIVC – Cost Comparison (directly supported camshaft design)

The study is further extended to Cummins L9 engine valvetrain as shown in **Table 0-7**, which has type V valvetrain i.e., pushrod mechanism. The components under study are slightly different from Cummins X15 components. Duramax 6.6L engine is taken as basis to cost rocker arm components whereas for Hydraulic roller lift mechanism CDA design provided by Eaton, specific to X15 engine is considered. Some of the key distinctive features of type V valvetrain compared to type III valvetrain are as follows:

1. No rocker shaft, brake rocker arm and engine braking OCVs
2. Camshaft located on the side of the engine and doesn't have extra lobes for brake rocker arm actuation
3. Simple intake and exhaust rocker arms owing to absence of rocker shaft

Components included as part of the push rod mechanism such as pushrod and hydraulic roller lifter are included in intake and exhaust rocker arm modules in **Table 0-7**.

Table 0-7: Cummins L9 Valvetrain Cost Breakdown

Subsystem	Sub-subsystem / Module	QTY	Unit Mass	Total Mass	Mass Total Percent "%"	Unit Cost	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain			kg	kg	%	US $	US $	%
01	Exhaust Bridge Module	6	0.050	0.300	0.92%	1.13	6.80	1.32%
02	Intake Bridge Module	6	0.050	0.300	0.92%	1.13	6.80	1.32%
03	Exhaust Rocker Arm Module	6	0.516	3.094	9.54%	17.72	106.31	20.57%
05	Intake Rocker Arm Module	6	0.530	3.178	9.80%	17.81	106.85	20.68%
08	Cam Shaft	1	18.050	18.050	55.64%	130.43	130.43	25.24%
09	Other Valvetrain Modules			7.516	23.17%		137.25	26.56%
10	Assembly			0.000	0.00%		22.26	4.31%
Total Cost				32.44	100%		516.70	100%
Cost per cylinder = $86.12								

Table 0-8 provides the TMC for 9L Engine valvetrain with Cylinder Deactivation system installed on all 6 cylinders. CDA capsule replaces the conventional hydraulic roller lifter placed under the push rod. Oil control module consists of an integrated mounting module (installed on the side of the engine), 6 OCVs and cylinder block machining required for creating oil passages.

Table 0-8: 9L Engine Valvetrain w/ CDA Cost Breakdown

Subsystem	Sub-subsystem / Module	QTY	Unit Mass	Total Mass	Mass Total Percent "%"	Unit Cost	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain			kg	kg	%	US $	US $	%
01	Exhaust Bridge Module	6	0.050	0.300	0.89%	1.13	6.80	1.02%
02	Intake bridge Module	6	0.050	0.300	0.89%	1.13	6.80	1.02%
03	Exhaust Rocker Arm Module	6	0.564	3.382	10.06%	21.32	127.92	19.05%

05	Intake Rocker Arm Module	6	0.578	3.466	10.31%	21.41	128.46	19.13%
06	Oil Control Module			3.972	11.82%		108.05	16.13%
08	Cam Shaft	1	14.578	14.578	43.37%	130.43	130.43	19.47%
09	Other Valvetrain Modules			7.616	22.66%		138.74	20.71%
10	Assembly			0.000	0.00%		22.62	3.38%
Total Cost				33.61	100%		669.83	100%
Cost per cylinder = $111.64								

Based on the two tables provided above, the NITMC to install Cylinder Deactivation System in all 6 cylinders of 9L type V valvetrain is $153.13. **Table 0-9** shows module by module comparison of the cost for Baseline vs CDA technologies. 9L Engine Type V Valvetrain Baseline vs CDA – Cost Comparison.

Table 0-9: 9L Engine Type V Valvetrain Baseline vs CDA – Cost Comparison

Cost Comparison (9L Engine Valvetrain) (Baseline vs CDA)				
ID	**Module**	**Baseline**	**CDA**	**Diff.**
1	Exhaust Bridge Module	$6.80	$6.80	
2	Intake Bridge Module	$6.80	$6.80	
3	Exhaust Rocker Arm Module	$106.31	$127.92	($21.62)
4	Brake Rocker Arm Module			
5	Intake Rocker Arm Module	$106.85	$128.46	($21.62)
6	Oil Control Module		$108.05	($108.05)
7	Rocker Shaft			
8	Cam Shaft	$130.43	$130.43	
9	Intake Valve	$26.18	$26.18	
	Exhaust Valve	$29.86	$29.86	
	Valve cover	$40.86	$40.86	
	Valve spring	$29.05	$29.05	
	Retainers, Cotters, Seats	$11.30	$11.30	
	Harness		$1.49	($1.49)
10	Assembly of all Components	$22.26	$22.62	($0.36)
Total		**$516.70**	**$669.83**	**($153.13)**

1. INTRODUCTION

1.A. Objective and Background

The overall goal of this work assignment is to provide a detailed technology cost assessment to variable valve actuation technologies such as Cylinder Deactivation and Late Intake Valve Closing. The selected baseline ICE for the analysis i.e., Cummins X15 is one of North America's most popular heavy-duty engines, and the only engine offered as an option by nearly every major Class 8 truck manufacturer.

The requested technology cost assessment is a detailed, transparent, bottom-up analysis employing an activity-based costing approach. Key cost analysis boundary conditions and assumptions include high product maturity, manufacturing in the United States, and production volume that includes cross-platform sharing capability for each individual component under consideration. The technology costs developed are referred to as Total Manufacturing Costs (TMC) and are inclusive of supplier component and assembly costs to the OEM and OEM Labor and Manufacturing Overhead to assemble the components to the engine. The TMC does not include OEM Indirect Manufacturing Costs (e.g. Corporate Overhead, SG&A, R&D, Tooling, etc.). Additional details on analysis boundary assumptions and cost factors are covered below in Section **1.D**.

Though any technology that has the potential to improve efficiency of engine / reduce emissions can either reduce the engine displacement or eliminate auxiliary modules (ex: EGR), the current study is limited to evaluating the incremental cost associated with installing new technologies to existing valvetrain modules. Understanding the cost impact and performance improvements, as they relate to criteria air pollutant emission reduction, facilitates EPA's assessment on which engine technologies are potentially of better value (i.e., Value = Technology Cost / Emissions Reduction). The cost information tabulated by these types of studies, along with technology performance metrics gathered from supporting studies, is leveraged to create technology packages used in EPA's cost effectiveness analyses, which form part of a Regulatory Impact Analysis used in future mobile source criteria air pollutant regulations.

The most sought out technology packages for EPA's Cleaner Trucks Initiative (CTI) are those which provide the largest improvement towards reducing NO_x emissions at the lowest possible cost and with either no impact on GHG emissions or a net reduction in GHG emissions. Both CDA and LIVC are strategies used for catalyst warmup and maintaining catalyst temperatures with potential for modest reductions in fuel consumption and CO_2 emissions. Both strategies reduce air aspiration through the engine at low BMEP. The overall goal is to maintain SCR temperatures at or above approximately 200°C[3] to allow urea dosing and decomposition to NH_3 without the deposit formation of urea salts on the urea injector and on catalyst system surfaces within the aftertreatment system. Both CDA and LIVC are technologies that, when combined with other changes (heated urea dosing, increased initial idle speed, changes to combustion phasing, EGR cooler bypass, etc.) can allow urea dosing and low temperature NH_3 storage at operating conditions where this was not previously possible, and thus extend NO_x control to most (or all) operating conditions including idle or near-idle with typical accessory loads. The key difference between these two strategies is that CDA completely removes airflow from a few cylinders with average exhaust temperature increment of 150°C to 250°C[4] in the 1.3–5.1 bar BMEP load range, while LIVC reduces airflow from all cylinders with up to 60°C[5] hotter exhaust temperatures (light load – 1200RPM, 2.5bar BMEP) and with potential for increasing exhaust temperature over a broader area of engine operation.

Production stock hardware, when available, is the preferred method to complete cost assessments of this nature. The teardown approach helps eliminate assumption-making in terms of component attributes (e.g. mass, size, material specifications, finish specifications, etc.) and integration challenges into the baseline ICE. Further, procuring a production stock valvetrain exhibiting the advance technology helps validate the viability of combining multiple technologies into one ICE application. For components that still have not reached a final production design, detailed CAD parts drawings were used to develop cost estimates.

1.B. Cost Analysis Terminology

The costs developed in this analysis are referred to as either Total Manufacturing Costs (TMC) or Net Incremental Total Manufacturing Costs (NITMC). In this analysis, the TMC is the full or absolute manufacturing cost of components, modules and engine subsystems. This includes both external costs, for purchased components and assemblies from suppliers, as well as internal costs for manufacturing operations performed by the OEM. The TMC strategy is employed when a full or absolute cost is required. Conversely the NITMC is a differential cost assessment used when comparing two technologies. This is typically the approach when evalauting a new or advanced technology relative to a baseline technology. If the two technologies are similar, only the differences are evaluated to arrive at the NITMC. If the two technolgies are significantly different, full or complete TMCs are calculated for each technology, the difference equal to the NITMC.

The cost elements included in a standard TMC model are broken out into three categories (**Figure 1-1** below). Total Direct Manufacturing Cost (TDMC) includes material, labor and manufacturing overhead cost contributions. The Total Indirect Manufacturing Cost (ITMC), also refered to as markup, includes end-item scrap expenses, selling, general and administrative (SG&A) expenses, profit, and engineering, design, and testing (ED&T) expenses. The final category is packaging costs.

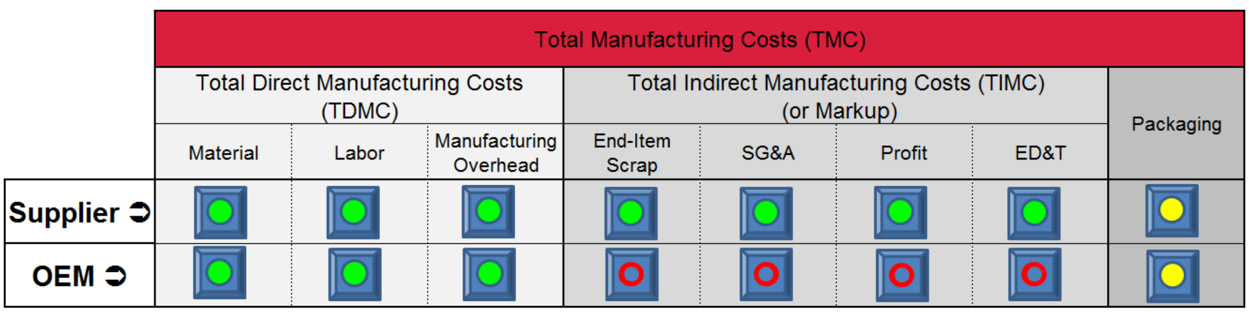


Figure 1-1: Total Manufacturing Cost Elements

The cost assessment approach assumes common boundary conditions (e.g. production volume, timeframe, manufatcuring region, etc.) for all technologies evaluated in the assessment. The objective is to provide a level playing field for comparion. In addtion the analysis strives to understand the cost differences between the evaluated technologies when the technologies are considered mature and at high production volumes. The reason for this is to promote technologies which are considered better value when they are at their peak volumes offering better long-term value. That said, although the costs are calculated using 2019 / 2020 cost elements (i.e., material, labor and manufatcuring overhead costs), the production assumptions and indirect manufatcuring costs are based on mature production assumptions. To adjust these new advanced technology costs to “today’s dollars”, reverse learning factors may be applied. The application of these learning factors is outside of the scope of this project. It is assumed that Eaton’s CDA and Mechadyne’s LIVC more or less has the same technology maturity and hence has same learning factors. We estimate the end cost to OEM to install these modules might be in the range of 1.5 times the evaluated should-cost.

In additon, no OEM Indirect Manufacturing Costs are applied to the FEV calculated values (as shown in **Figure 1-1** above). If a Tier 1supplier develops a technology, and that technology is integrated into an OEM's engine, the OEM will have indirect costs associated with adapting the technology into the engine including tooling costs, ED&T costs, corporate overhead costs, etc. These cost are generally accounted for by applying a Retail Price Equivalent (RPE) factor, or in EPA assessments, sometimes referred to as an Indirect Cost Multiplier (ICM).

1.C. Study Methodology

The costing methodology, databases and supporting worksheets used in the cost analysis are generally the same as those used in previous EPA cost assessment studies. Updates to improve fidelity and transparency are made on a regular basis supporting continuous improvement initiatives. In many cases, updates and improvements in the methodology and documentation have been the direct result of the external EPA peer review process.

Presented below, and with the aid of **Figure 1-2**, is a brief overview of the FEV costing methodology. A detailed review of the FEV methodology can be found in EPA report (June 2015) "Mass-Reduction and Cost Analysis – Light-Duty Pickup Truck Model Years 2020-2025"[6].

The FEV costing methodology is executed in four phases. Found below is a high level description of the types of tasks completed in each phase.

1. **Phase 1 Tasks**
    - 1.1. Research, review and select technology representing leading edge ICE technology becoming industry standard for analysis.
    - 1.2. Define the cost analysis boundary conditions (e.g., volume, manufacturing location, mark-up rates, and manufacturing cost structures). The boundary conditions are critical for establishing a consistent framework for all absolute costs and net incremental total manufacturing cost comparison studies. The boundary conditions also provide the DNA for comparison to external cost analyses, helping assess variation where it may exist.
    - 1.3. Top level disassembly of select valvetrain subsystem. In general the engine subsystem is disassembled in the reverse order of how it was assumed to be assembled. A comparison bill of material (CBOM), loaded with basic T1 and OEM part attributes, and linked to disassembly photographs, tracks the disassembly sequence. The CBOM has a manufacturing and design/product structure section to track key cost driving information from a materials, design and processing perspective.
    - 1.4. A cross functional team updates the BOM with design and manufacturing attributes for all T1 and OEM components. This information provides the required information for commodity and detailed cost calculations.

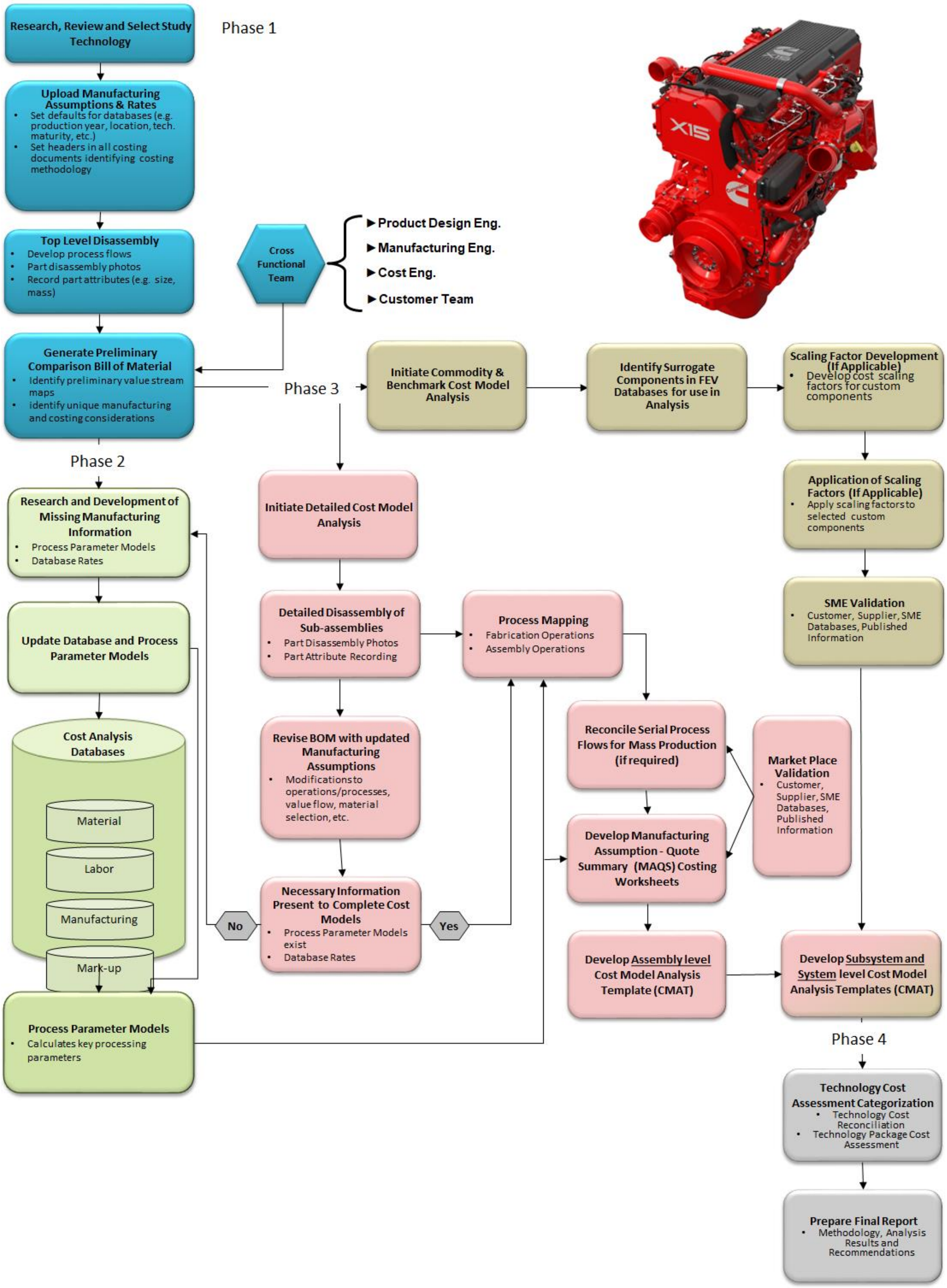


Figure 1-2: Costing Methodology Process Flow

2. Phase 2 Tasks

2.1. Based on the boundary conditions for the analysis, and the attributes tracked in the CBOM, a team begins to update the costing databases and process parameter models unique to the analysis.

2.2. The databases contain all costing data and rates used to support the analysis. There are five primary databases, material, labor, manufacturing overhead, mark-up (e.g., end item scrap, profit, SG&A, R&D) and packaging. For each database, secondary models exist providing the calculations used to develop the rates. For example, in the labor rate database, loaded labor rates are calculated by applying contributions (based on industry classification) for indirect labor, maintenance repair and other labor (MRO), and fringe. In the labor database, rates are first categorized by primary industry classification (e.g., plastics, rubber, metal fabrication, vehicle parts manufacturer, vehicle manufacturers, etc.) followed by standard occupation classification (e.g., general assembly operator, metal press operator, mold press/extrusion operator, CNC operator, etc.). In addition, labor rates for selected countries and selected regions within a country are captured. In appendix, **Figure 8-8** shows the material, labor and MOH rates used for developing a should-cost estimate for exhaust bridge.

2.3. Process parameter models are custom models used to calculate key processing factors such as material usage, equipment selection, tool size and complexity, order of operations, and cycle times. Process parameter models range from simplistic models used to calculate injection mold tonnage and cycle times to complex sand cast and machining models. Based on the model maturity and complexity, various levels of user knowledge are required.

2.4. As T1 and OEM assemblies are disassembled to the raw component levels, further updates to the databases and process parameter models are often required to support new material or advance manufacturing processes.

3. Phase 3 Tasks

3.1. The cost analysis begins in Phase 3. Based on the type of components under evaluation, the cost engineering team determines if commodity costing or detail costing is required for each component. Commodity costing is generally reserved for low-impact type components and/or components for which pricing exists in a commodity database of similar components based on prior cost studies or acquired quotes. Generally, commodity-type costing is reserved for fastening hardware (nuts, bolts, washers, seals, etc.) and mass-produced, lower dollar value, mature components. Examples of these types of components include standard pressure or temperature sensors, spark plugs, small wire harnesses, suspension bushings, and isolators. Custom vehicle specific components and/or moderate to high impact type components are costed using detailed cost models. In appendix, **Figure 8-7** shows manufacturing process flow steps developed for exhaust bridge in baseline valvetrain.

3.2. Manufacturing Assumption and Quote Summary (MAQS) worksheets are generated for all parts undergoing the cost analysis. The MAQS details all cost elements making up the final TMC: material, labor, manufacturing overhead/burden, end item scrap, SG&A, profit, ED&T, and packaging. The high-level costing process flow, identifying key documents and tools, is shown below in **Figure 1-3**.

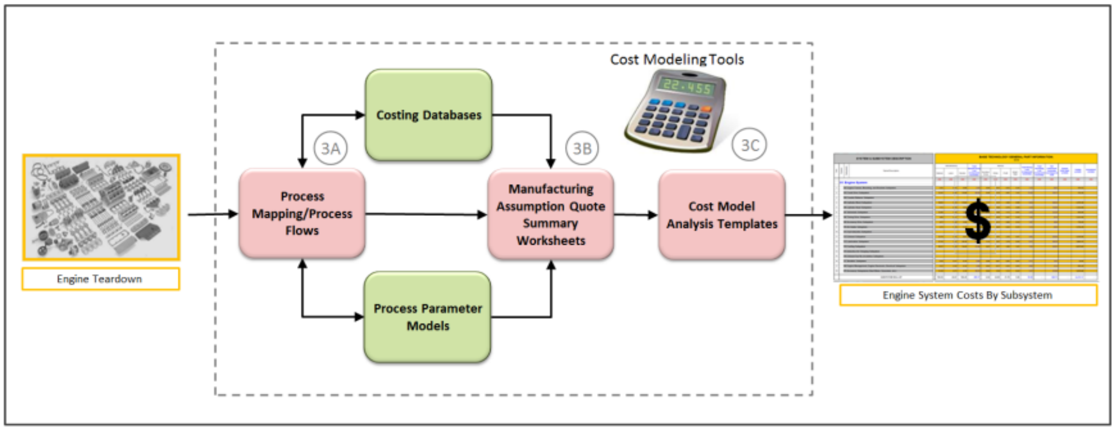


Figure 1-3: Overview of FEV Costing Flow

3.3. Parts with high or unexpected cost results are subjected to a marketplace cross-check, such as comparison with supplier price quotes or wider consultation with company and industry resources (i.e., subject matter experts) beyond the Cross functional team (CFT)

3.4. As component costs are developed, they are summed into cost model analysis templates (CMATs) at the assembly/sub-subsystem, subsystem, and system level. For example, the TMC of a cam roller can be found in a rocker arm assembly/sub-subsystem. The TMC of the cam roller and other rocker arm module components (e.g., center sleeve, shaft, resting joint) can be found in the same subsubsystem.

3.5. Analysis data is bundled and tracked using the CMAT structure to evaluate cost and mass at different product struture levels as well as to support the comparison of alternative technologies at different levels.

4. Phase 4 Tasks

4.1. At the conclusion of Phase 3, final TMC models exist for all layers of the product structure. From a technology TMC perspective, additional cost accounting is still required. This is the result of some components and assemblies having primary functionality as well as integrated secondary functionality. For example, the cylinder head has added machined features to support the exhaust bridge post for the CDA module. These features were added to support the integration of the CDA exhaust bridge and thus from a cost accounting perspective should be added to the CDA valve train technology cost.

4.2. At the completion of the technology cost reconciliation step above, Net Incremental Total Manufacturing Cost (NITMC) assessments were completed for the two comparison configurations discussed in Section **1.A** (CDA and LIVC).

4.3. Baseline costing is scaled further to evaluate valvetrain cost for 9L and 6.7L engine variants (Cummins). The same methodology is applied to CDA and LIVC technologies to capture the NITMC in each of these engine variants.

4.4. Preparation of the final report highlighting the methodology and results.

1.D. Analysis Boundary Conditions

When conducting an analysis for the various technology configurations, a set of boundary conditions and assumptions are made in order to establish a consistent framework for all costing. The assumptions can be broken into universal and specific case study assumptions. As highlighted above, without these well documented boundary conditions and assumptions, the derived costs have little to no value. This is true for the results generated within the study as well and when comparing results to external studies.

The universal assumptions apply to all technology cost evaluated within this analysis. Listed in **Table 1-1** are the fundamental assumptions which are similar to those applied in all previous studies completed for EPA by FEV.

The specific case study assumptions are those unique to a given technology configuration. These include items like manufacturing processing assumptions, automation versus semi-automation, direct labor utilization, weekly operation assumptions (days, shifts, hours, etc.) and Tier 1 in-house manufacturing versus Tier 2/3 purchase part assumptions. These assumptions are captured in the specific Manufacturing Assumption – Quote Summary worksheets for each component or assembly evaluated in detail.

Production volume plays a key role in cost analysis as it dictates the material rates, equipment and labor utilization and process efficiency for each of the components. As many of the baseline engine valvetrain components can be used in other engine platforms, a thorough research is made across all the engines offered in North America to assign the correct production volume for each component. Heavy-duty and Medium-Duty engines from Cummins (X15, X12, L9, B6.7), Detroit Diesel (DD16, DD15, DD13, DD8, and DD5), and Navistar (A26), GM 6.6L, Paccar (MX-13, MX-11), Volvo (D13M, D11M) and Ford Powerstroke 6.7 are considered for determining the right boundary condition for each component.

Table 1-1: Summary of Universal Cost Analysis Boundary Conditions and Assumptions

Item	Description	Universal Case Study Assumptions
1	Incremental Production Tooling Costs (Not included within the scope of this cost analysis)	A. Production Tooling costs, for both OEM and suppliers, are not included in the analysis. The tooling costs are addressed by the EPA applied ICM factor. B. Analysis assumes all tooling is owed by OEM C. Tooling includes items like stamping dies, plastic injection mold, die casting molds, weld fixtures, assembly fixtures, gauges, etc.

2	Product/Technology Maturity Level	A. Mature technology assumption, as defined within this analysis, includes the following: a. Well-developed product design b. Products in service for several years at high volumes c. Significant market place competition B. Mature Technology assumption establishes a consistent framework for costing. For example, a defined range of acceptable mark-up rates. a. End-item-scrap 0.3-0.7% b. SG&A/Corporate Overhead 6-7% c. Profit 4-8% d. ED&T (Engineering, Design and Testing) 0-6% C. The technology maturity assumption does not include allowances for product learning. Application of a **learning curve** to the calculated incremental direct manufacturing cost is handled outside the scope of this analysis.
3	Selected Manufacturing Processes and Operations	A. All operations and processes are based on existing standard/mainstream Industrial practices. B. No additional allowance is included in the incremental direct manufacturing cost for manufacturing learning. Application of a **learning curve** to the developed incremental direct manufacturing cost is handled outside the scope of this analysis.
4	Annual Capacity Planning Volume	30,000 Engines
5	Supplier Manufacturing Location	United States of America
6	OEM Manufacturing Location	United States of America
7	Manufacturing Cost Structure Timeframe (e.g. Material Costs, Labor Rates, Manufacturing Overhead Rates)	2019/2020 Production Year Rates
8	Packaging Costs	A. Estimated on Tier One (T1) supplier level components from surrogate EPA studies. B. For Tier 2/3 (T2/T3) supplier level components, packaging costs are included in T1 mark-up of incoming T2/T3 incoming goods.
9	Shipping and Handling	A. T1 supplier shipping costs covered through application of the Indirect Cost Multiplier (ICM) discussed above. B. T2/T3 to T1 supplier shipping costs are accounted for via T1 mark-up on incoming T2/T3 goods.

10	Intellectual Property (IP) Cost Considerations	Where applicable IP costs are included in the analysis. Based on the assumption that the technology has reached maturity, sufficient competition would exist suggesting alternative design paths to achieve similar function and performance metrics would be available minimizing any IP cost penalty.
11	Material Cost Reductions (MCRs) on analyzed hardware	Only incorporated on those components where it was evident that the component design and/or selected manufacturing process was chosen due to actual low production volumes (e.g. design choice made to accept high piece price to minimize tooling expense). Under this scenario, assumptions where made, and cost analyzed assuming high production volumes.
12	Operating and End-of Life Costs	No new, or modified, maintenance or end-of-life costs, were identified in the analysis.
13	Stranded Capital or ED&T expenses	No stranded capital or non-recovered ED&T expenses were considered within the scope of this analysis. It was assumed the integration of new technology would be planned and phased in minimizing non-recoverable expenses.

1.E. Structure of This Report

The report is structured in six different sections (including this, Section 1) with Appendices. The sections as they respectfully breakdown include:

Section 2: Overview of different valvetrain technologies

Section 3: Baseline valvetrain sub-subsystem classification overview, component specifications, cost review, scaling methodology and cost of valvetrain for other engine variants

Section 4: Cylinder Deactivation module component specifications, cost review and cost of valvetrain for other engine variants

Section 5: FlexValve module component specifications, cost review and cost of valvetrain for other engine variants

Section 6: Comparison of Baseline vs CDA vs FlexValve valvetrain with supporting design and manufacturing attributes

Section 7: Summary and Conclusion

Appendices: Teardown BOM, Part pictures, Glossary and References

2. VALVETRAIN TECHNOLOGIES OVERVIEW

2.A. Engine Compression Braking

The baseline valvetrain is a type III single overhead cam type configuration that has two oil control modules for compression release braking. Apart from the usual intake and exhaust rocker arms, baseline valvetrain includes brake rocker arms which opens the exhaust valve near top dead center for compression release braking. **Figure 2-1** shows the schematic of a brake rocker arm where pressurized oil from the Oil control module pushes the exhaust valve bridge and opens the exhaust valve at the end of the compression stroke.

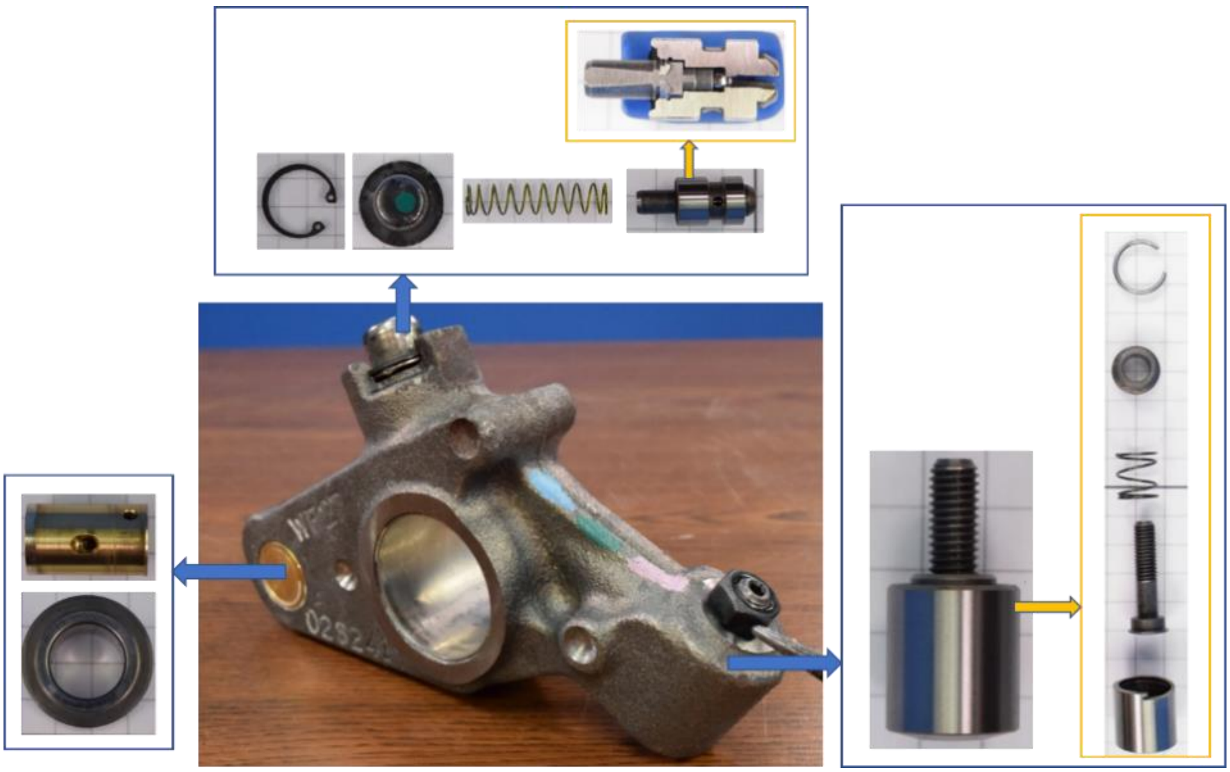


Figure 2-1: Brake Rocker Arm Design Schematic

2.B. Cylinder Deactivation System

Cylinder Deactivation allows an engine to reduce fuel consumption, air mass flow through the engine, and emissions during light-load operation. It is achieved by keeping the intake and exhaust valves closed for specific cylinder(s). CDA capsules reside in intake and exhaust rocker arms and allow valve closing by using a spring-loaded latch mechanism. Along with the two oil control valves for engine braking, CDA requires six oil control valves (one per cylinder) and subsequent machining of the rocker arm shaft to mount these extra CDA valves. **Figure 2-2** shows the schematic of Eaton's CDA capsules that are installed in Intake and Exhaust rocker arms for cylinder deactivation in a type III valvetrain. As shown in the figure, the capsule consists of a latch and spring, which locks and pulls the E-Foot Pivot up thereby closing the intake and exhaust valve and deactivating the respective cylinder.

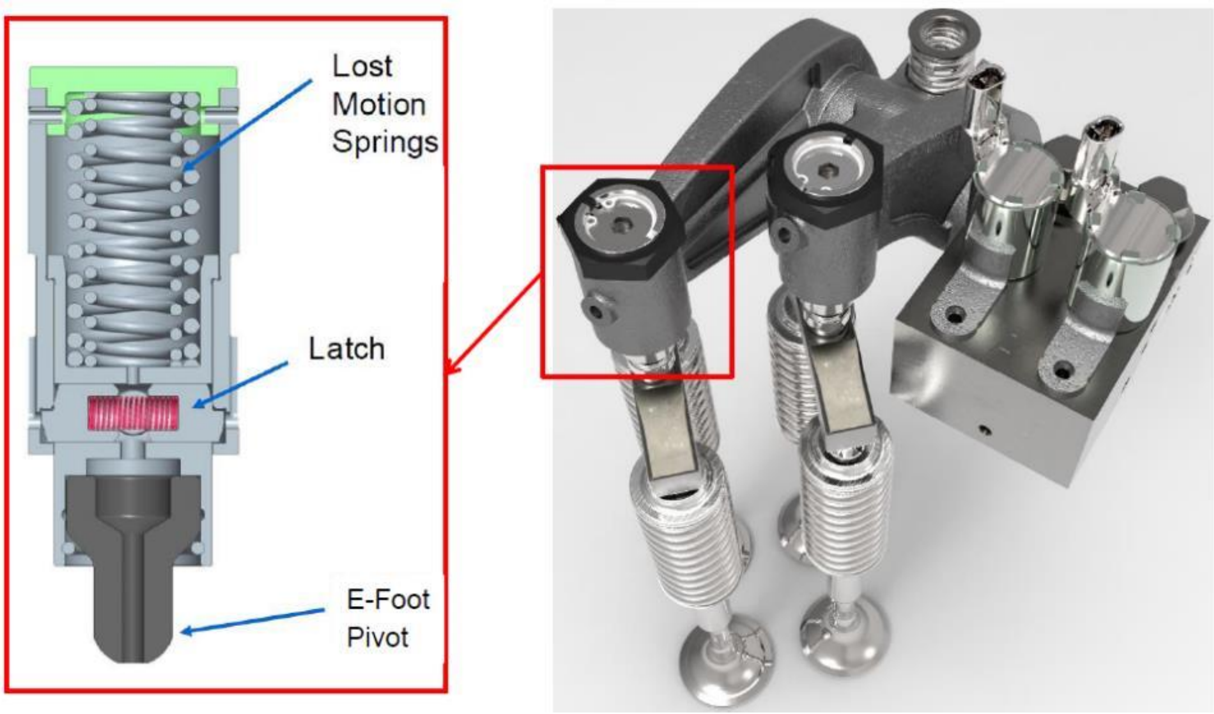


Figure 2-2: CDA Capsule in type III Valvetrain

The present CDA setup requires one OCV per cylinder such that the OCV deactivates the intake and exhaust valve. The method in which the engine transitions from normal six cylinders firing to CDA is typically the following: an oil pressure signal is sent to the intake and exhaust deactivation devices following the intake event (or once the intake is in the latch restricted state) such that the next exhaust event is deactivated (and likewise the next intake event. This function is commonly referred to as entering CDA with "high pressure trapping"**. Figure 2-3** shows all the modules in Eaton's CDA system.

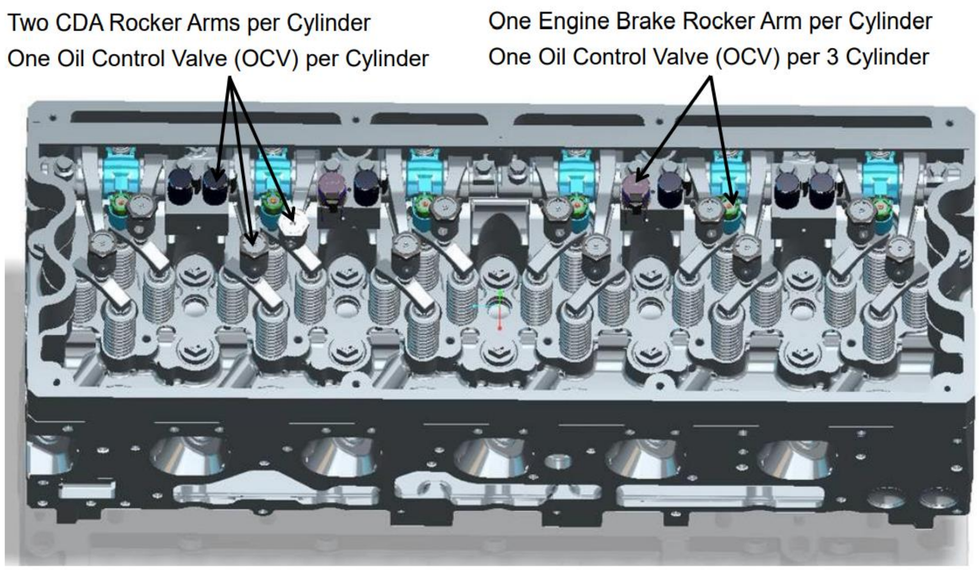


Figure 2-3: CDA Valvetrain – All Modules

An alternative to "high pressure trapping" is "low pressure trapping" that has been reported in the industry. In this method, the control strategy from normal six cylinders firing mode to CDA would enter CDA following the last exhaust event. This adds some complexity since the intake event typically opens slightly before the exhaust closes. In order to enable "low pressure trapping," one method would be to double the number of OCV's such that there is independent control of the intake and exhaust events for each cylinder. Likewise, the oil passages in the rocker arms would need to be separated.

Figure 2-4 shows the schematic of Eaton's CDA capsules that are installed under pushrods replacing traditional hydraulic roller lifters used in type V valvetrains. Similar to the design shown in **Figure 2-2**, this module includes latch and spring mechanism which locks and prevents pushrod movement, thereby deactivating the respective cylinder.

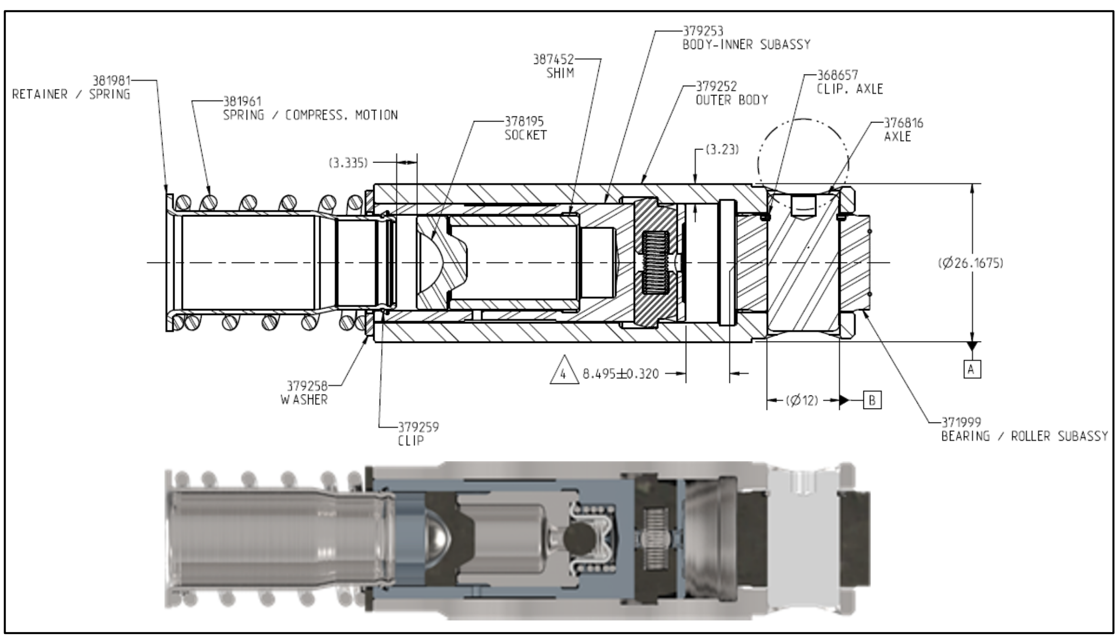


Figure 2-4: CDA Capsule in type V valvetrain

2.C. FlexValve System for Late Intake Valve Closing

FlexValve is a continuously variable mechanical valve lift system (CVVL). The system consists of an assembled camshaft with two groups of cam lobes that are movable relative to each other, a compound rocker system which “sums” the movable cam lobes and a hydraulic actuator (similar to a cam phaser). The actuator controls the relative position of the two groups of cam lobes which, through the action of the “summing” rocker system, provides control of intake valve closing angle and valve lift.

Variable valve lift systems vary the height of valves in order to control airflow through the engine and can improve performance, fuel economy and reduce emissions. Both the intake and exhaust centerline timings can be controlled to give optimum engine performance over the complete operating range. This technology can realize fuel consumption benefits of up to 5% and NOx reduction up to 25% (engine-out).

Figure 2-5 shows the schematic of Mechadyne’s FlexValve Rockers. It consists of FlexValve Rocker Assembly and Output Rocker Assembly linked by a pivot shaft. The output rocker has a pair of cam rollers that act on the fixed cam lobes (responsible for opening of the valves). The Single Roller in FlexValve rocker acts on a moving cam lobe and is responsible for closing of the valves. The control spring ensures that the twin rollers on the output rocker assembly remains in contact with their respective fixed cam lobes.

Figure 2-6 and **Figure 2-7** shows the schematic of Mechadyne’s FlexValve Camshaft, which consists of 12 fixed cam lobes meshing on Output rocker cam rollers and 6 moving cam lobes meshing on FlexValve rocker rollers. The moving cam lobes are connected to an inner drive shaft by drive pins that pass-through slots in the tube. A core plug is fitted into the rear of the tube to seal the internal oil gallery.

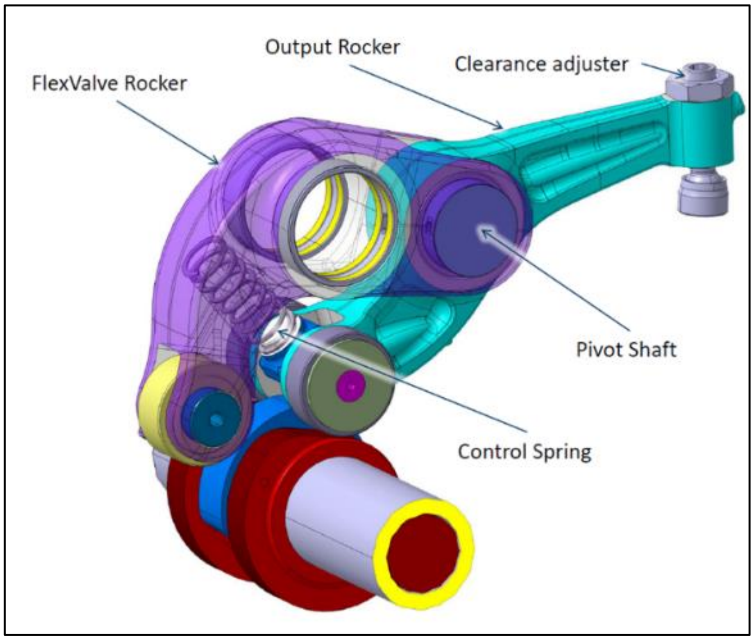


Figure 2-5: FlexValve Rocker Design Schematic

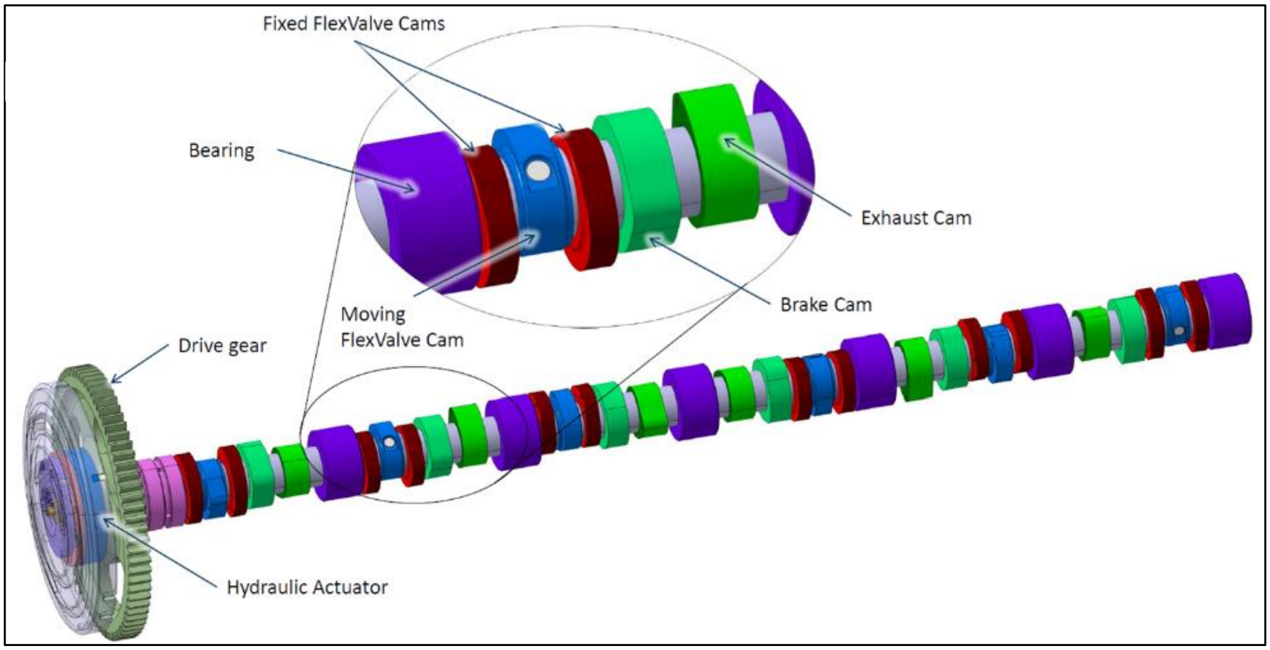


Figure 2-6: FlexValve Camshaft Design Schematic-1

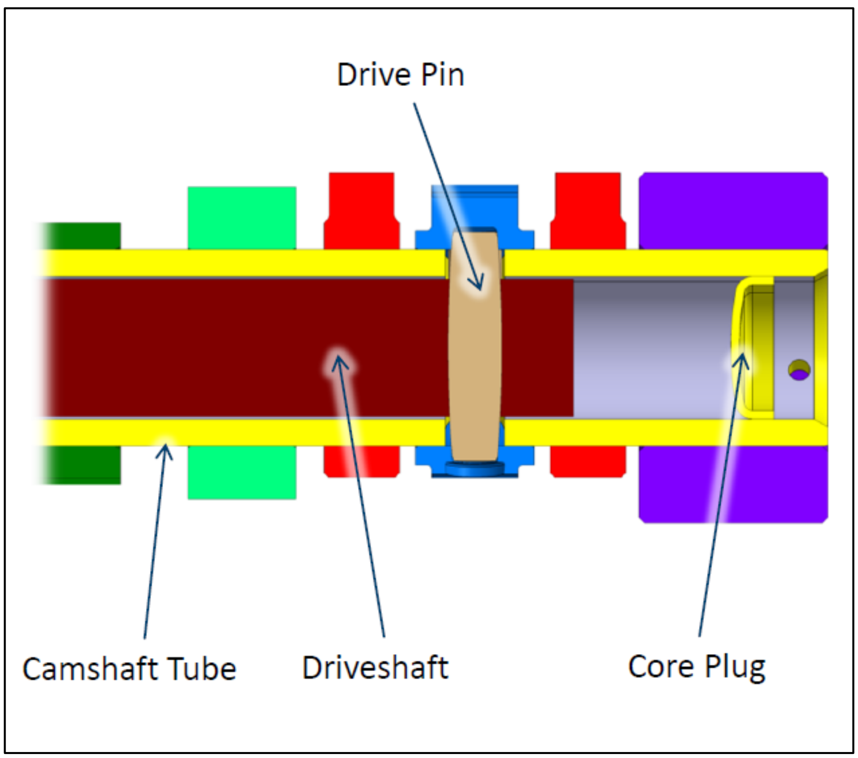


Figure 2-7: FlexValve Camshaft Design Schematic-2

3. BASELINE TECHNOLOGY ANALYSIS

During the Cummins X15 Valvetrain teardown, a comparison bill of materials (CBOM) was created. The manufacturing bill of material portion of the CBOM is initially populated during the teardown. Components and assemblies are loaded into the CBOM as they are removed from the valvetrain, inferring the sequence they were likely assembled to the engine. Tracking the part removal sequence supports the Valvetrain assembly sequence assumptions made during the assembly cost build-up portion of the analysis.

Parts are removed as components, assemblies/sub-subsystems or modules. The process is to remove content at the same level as it may have been installed on the valvetrain during engine final assembly. In this situation it as assumed that the subassemblies were either sub-assembled by the OEM, or outside T1 supplier off the final ICE assembly line. Once the sub-subsystems or modules are removed, they are disassembled further to a T1 or OEM purchased component. Identifying the value stream and various levels of value-add can be subjective in some cases, therefore the team does consult with subject matter experts to help identify typical industry practices. The CBOM is structured to capture these assumed levels of assembly which is required for building up the subassembly cost models.

Once the teardown is completed and the manufacturing portion of the CBOM is finalized, the categorization of modules begins, based on primary design functionality. This categorization helps identify where the largest contributions are from a cost perspective, summing up technology costs from a functionality perspective (e.g. oil control module, rocker arm module) and facilitates comparing similar functionality between two competing technologies (e.g. cost of Oil control module in baseline vs CDA installed valvetrain).

The team hopes this structured layout will facilitate the review of the parts and cost estimates developed for the Valvetrain technologies studied. The cost calculations below are based on the purchased production stock valvetrain. The costs modeled are considered absolute costs, not incremental or delta costs.

Table 3-1 below provides a listing of the modules / sub-subsystems listed under the Valvetrain subsystem. Each sub-subsystem has a corresponding note included to identify if components / assemblies were evaluated within the sub-subsystem as part of the Cummins X15 assessment. If sub-subsystems were not included in the analysis, it is likely the sub-subsystem was out of scope, or the parts within the sub-subsystem were not applicable in the studied application. It also provides cost breakdown of the entire valvetrain subsystem in terms of material, labor, overhead and indirect manufacturing costs.

Table 3-1: Cummins X15 Valvetrain Attribute and Cost Summary Overview

System:	Engine		
Subsystem:	Valvetrain		
Sub-Subsystem Categorization with Subsystem			
1	Exhaust Bridge Module	Included in Analysis	
2	Intake Bridge Module	Included in Analysis	
3	Exhaust Rocker Arm Module	Included in Analysis	
4	Brake Rocker Arm Module	Included in Analysis	
5	Intake Rocker Arm Module	Included in Analysis	
6	Oil Control Module	Included in Analysis	
7	Rocker Shaft	Included in Analysis	
8	Cam Shaft	Included in Analysis	
9	Intake Valve	Not Included in Analysis	
	Exhaust Valve	Not Included in Analysis	
	Valve cover	Not Included in Analysis	
	Valve spring	Not Included in Analysis	
	Spring Retainers, Cotters, Spring Seats	Not Included in Analysis	
	Harness	Included in Analysis	
10	Assembly of Entire Subsystem	Included in Analysis	
Key Attributes			
1	Single Overhead Camshaft with dedicated lobe for Compression Brake		
2	Two Oil Control Modules - each control oil flow for 3 cylinders		
3	Brake rocker arm includes a detent rocker lever to lock into rocker shaft		
4	Solenoid in Oil Control Module transfers pressurized oil to rocker arms		
5	Assumed to share components with X12 Engine valvetrain		
6	Intake and Exhaust rocker arms have cross-drilling for oil cooling		
Cost Structure			
Material	$ 188.24	EIS	$ 3.22
Labor	$ 54.20	SG&A	$ 41.89
Burden	$ 350.05	Profit	$ 38.66
TDMC	$ 592.48	ED&T	$ 15.37
		TIMC	$ 99.14
TMC	**$ 691.62**	**Subsystem Mass (kg)**	**58.05**
TDMC - Total Direct Manufacturing Cost, EIS - End Item Scrap, SG&A - Selling, General & Administrative costs, ED&T - Engineering, Design & Testing, TIMC - Total Indirect Manufacturing Cost, TMC - Total manufacturing Cost			

Cummins L9 engine is used as baseline to evaluate valvetrain cost for a type V valvetrain. FEV engine benchmark data is used to estimate cost for components of the Cummins L9 Engine valvetrain.

Table 3-2 below provides a listing of the modules / sub-subsystems listed under the Cummins L9 Valvetrain subsystem. It also provides cost breakdown of the entire valvetrain subsystem in terms of material, labor, overhead and indirect manufacturing costs.

Table 3-2: Cummins L9 Valvetrain Attribute and Cost Summary Overview

System:	**Engine**		
Subsystem:	**Valvetrain**		
Sub-Subsystem Categorization with Subsystem			
1	Exhaust Bridge Module	Included in Analysis	
2	Intake Bridge Module	Included in Analysis	
3	Exhaust Rocker Arm Module	Included in Analysis	
4	Brake Rocker Arm Module	Included in Analysis	
5	Intake Rocker Arm Module	Included in Analysis	
6	Oil Control Module	Included in Analysis	
7	Rocker Shaft	Included in Analysis	
8	Cam Shaft	Included in Analysis	
9	Intake Valve	Not Included in Analysis	
	Exhaust Valve	Not Included in Analysis	
	Valve cover	Not Included in Analysis	
	Valve spring	Not Included in Analysis	
	Spring Retainers, Cotters, Spring Seats	Not Included in Analysis	
	Harness	Included in Analysis	
10	Assembly of Entire Subsystem	Included in Analysis	
Key Attributes			
1	9L I6 Engine - OHV Pushrod Valvetrain (Type V)		
2	No Engine compression braking (but Cummins provides an add-on option)		
3	Engine braking is achieved using VGT based exhaust brake		
4	Includes hydraulic roller lifters to maintain zero lash		
5	Camshaft located on the side of the Engine block		
6	Assumed to share components with Cummins B6.7 Engine valvetrain		
7	Simple intake and exhaust rocker arms owing to absence of rocker shaft		
8	No extra lobes on Camshaft for brake rocker arm actuation		
Cost Structure			
Material	$ 100.24	EIS	$ 2.24
Labor	$ 59.20	SG&A	$ 29.15
Burden	$ 287.75	Profit	$ 26.90
TDMC	$ 447.19	ED&T	$ 11.21
		TIMC	$ 69.50
TMC	**$ 516.70**	**Subsystem Mass (kg)**	**32.44**

TDMC - Total Direct Manufacturing Cost, EIS - End Item Scrap, SG&A - Selling, General & Administrative costs, ED&T - Engineering, Design & Testing, TIMC - Total Indirect Manufacturing Cost, TMC - Total manufacturing Cost

The Cost Model Analysis Templates (CMAT) for the Valvetrain Subsystem shown in **Table 3-3**, provide cost breakdowns for key components evaluated in the Cummins X15 engine valvetrain. For each subsystem, multiple sub-subsystems were evaluated and the CMAT summarizes the sub-subsystem / module contributions to the overall subsystem.

Along with material, labor, overhead and indirect cost breakdown, the CMAT also provides quantity and mass for each of the analyzed components.

Table 3-3: Cummins X15 Valvetrain Cost Summary Sheet

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Total Mass	Mass Total Percent "%"	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain				kg	%	US $	%
01	Exhaust Bridge Module		6	0.884	1.52%	14.94	2.16%
1	Pin_Exhaust_Bridge	8620 Steel, Machining	6	0.162	0.28%	5.62	0.81%
2	Exhaust_Bridge	8620 Steel, Forging	6	0.722	1.24%	9.31	1.35%
02	Intake Bridge Module		6	0.869	1.50%	8.66	1.25%
4	Intake_Bridge	8620 Steel, Forging	6	0.869	1.50%	8.66	1.25%
03	Exhaust Rocker Arm Module		6	4.267	7.35%	68.77	9.94%
5	Nut_Resting_Joint	Steel, Cold forge	6	0.056	0.10%	0.80	0.12%
6	Resting_Joint	E52100 Steel, Machining	6	0.226	0.39%	10.04	1.45%
7	Shaft_Cam_Roller	P5 Steel, Machining	6	0.281	0.48%	12.85	1.86%
8	Cam_Roller	E52100 Steel, Machining	6	0.482	0.83%	11.00	1.59%
9	Exhaust_Center_Sleeve	4140 Steel, Stamping	6	0.107	0.19%	2.24	0.32%
10	Exhaust_Rocker_Arm	Ductile-iron, Sand-Casting	6	3.114	5.36%	31.85	4.61%
04	Brake Rocker Arm Module		6	7.711	13.28%	91.41	13.22%
11	Brake_Nut_Resting_Nut	Steel, Cold forge	6	0.028	0.05%	1.19	0.17%
12	Brake_Resting_Assembly	E52100 Steel, Machining	6	0.385	0.66%	9.87	1.43%
13	Snap_ring_Oil_Flow	Alloy Steel, Stamping	6	0.007	0.01%	1.94	0.28%
14	Cap_Oil_Flow	Alloy Steel, Stamping	6	0.035	0.06%	2.07	0.30%
15	Spring_Oil_Flow	Steel, Coiling	6	0.010	0.02%	0.54	0.08%
16	Oil_Flow_Assembly	E52100 Steel, Machining & Assembly	6	0.140	0.24%	9.03	1.31%
17	Brake_Shaft_Cam_Roller	Bronze, Machining	6	0.437	0.75%	11.15	1.61%
18	Brake_Cam_Roller	E52100 Steel, Machining	6	0.482	0.83%	11.15	1.61%
19	Brake_Center_Sleeve	4140 Steel, Stamping	6	0.150	0.26%	2.38	0.34%
20	Brake_Rocker_Arm	Ductile-iron, Sand-Casting	6	6.036	10.40%	42.09	6.09%
05	Intake Rocker Arm Module		6	5.892	10.15%	71.33	10.31%
21	Intake_Nut_Resting_Joint	Steel, Cold forge	6	0.055	0.10%	0.80	0.12%
22	Intake_Resting_Joint	E52100 Steel, Machining	6	0.226	0.39%	8.44	1.22%
23	Intake_Shaft_Cam_Roller	P5 Steel, Machining	6	0.281	0.48%	12.93	1.87%
24	Intake_Roller_Arm	E52100 Steel, Machining	6	0.482	0.83%	11.00	1.59%
25	Intake_Center_Sleeve	4140 Steel, Stamping	6	0.107	0.19%	2.25	0.32%
26	Intake_Rocker_Arm	Ductile-iron, Sand-Casting	6	4.740	8.17%	35.92	5.19%
06	Oil Control Module		2	1.064	1.83%	20.77	3.00%
27	Bolt_Oil_Control	Steel, Cold forge	2	0.009	0.02%	0.33	0.05%
28	Oring_Oil_Control	Rubber, Injection Molding	2	0.001	0.00%	0.01	0.00%
29	Small_Oring_Oil_Control	Rubber, Injection Molding	2	0.000	0.00%	0.01	0.00%
30	Filter_Oil_Control	Overmolded filter	2	0.001	0.00%	1.15	0.17%
31	Oil_Control_Cover	Plastic, Injection Molding	2	0.008	0.01%	1.08	0.16%

32	Cap_Oil_Control	Alloy Steel, Stamping	2	0.046	0.08%	0.77	0.11%
33	Oil_Control_Internals_Cover	Commodity	2	0.109	0.19%	3.27	0.47%
34	Dowel_Oil_Control	Stainless Steel, Machining	2	0.020	0.03%	1.32	0.19%
35	Pin_Holder_Plate	Powder Metal	2	0.037	0.06%	0.59	0.08%
36	Pin_oil_Control	Alloy Steel, Machining	2	0.001	0.00%	0.14	0.02%
37	Bracket_Oil_Filter	Alloy Steel, Blanking	2	0.029	0.05%	0.72	0.10%
38	Internal_Pin	Alloy Steel, Machining	2	0.005	0.01%	0.70	0.10%
39	Sleeve_Internal_Pin	Alloy Steel, Machining	2	0.002	0.00%	0.66	0.10%
40	Housing_Internal_pin	Al, Die-cast	2	0.079	0.14%	1.09	0.16%
41	Mounting_Oil_Control	Powder Metal	2	0.718	1.24%	8.94	1.29%
07	Rocker Shaft		2	6.044	10.41%	64.96	9.39%
42	Rocker_Arm_Rod	4140 Steel, Machining	2	6.044	10.41%	64.96	9.39%
08	Cam Shaft Module		1	21.100	36.35%	144.86	20.94%
43	Cam_Shaft	Steel, Machining	1	17.000	29.28%	109.99	15.90%
44	Cam gear	8620 Steel, Forging	1	3.900	6.72%	24.91	3.60%
44	Camshaft Sensing	Powder Metal	1	0.200	0.34%	9.96	1.44%
09	Other Valvetrain Modules			10.222	17.61%	184.57	26.69%
44	Intake Valve	Steel, Forging	12	0.660	1.14%	34.91	5.05%
44	Exhaust Valve	Steel, Forging	12	0.648	1.12%	39.81	5.76%
44	Valve cover	PA66, Injection Molding	1	6.434	11.08%	54.48	7.88%
44	Valve spring	Steel, Coiling	24	1.296	2.23%	38.74	5.60%
44	Retainers, Cotters, Seats	NA	24	0.984	1.70%	15.06	2.18%
44	Harness	-----	1	0.200	0.34%	1.57	0.23%
10	Assembly			0.000	0.00%	21.36	3.09%
A	Assembly of all Components	Assembly	1	0.000	0.00%	21.36	3.09%
Total Cost				58.05	100%	691.62	100%

The Cost Model Analysis Templates (CMAT) for the Valvetrain Subsystem shown in **Table 3-4**, provide cost breakdowns for key components evaluated in the Cummins L9 engine valvetrain. Pushrod and hydraulic roller lifter modules (Housing) are included in intake and exhaust rocker arm modules. In appendix, **Figure 8-5** highlights components that are unique to type V valvetrain as compared to type III valvetrain.

Table 3-4: Cummins L9 Valvetrain Cost Summary

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Total Mass	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain				kg	US $	%
01	Exhaust Bridge Module			0.300	6.80	1.32%
1	Exhaust Bridge	8620 Steel, Forging	6	0.300	6.80	1.32%
02	Intake Bridge Module			0.300	6.80	1.32%
2	Intake Bridge	8620 Steel, Forging	6	0.300	6.80	1.32%
03	Exhaust Rocker Arm Module			3.094	106.31	20.57%
3	Exhaust Rocker Arm	4140 Steel, Sand-Casting	6	1.218	15.97	3.09%
5	Pushrod	S-Steel-304, Machining	6	0.528	26.80	5.19%
6	Housing	8620 Steel, Machining	6	0.925	23.86	4.62%
7	Swivel Rod	E52100 Steel, Machining	6	0.129	13.68	2.65%
8	Bearing-1	E52100 Steel, Machining	6	0.144	12.99	2.51%
9	Bearing-2	E52100 Steel, Machining	6	0.078	12.69	2.46%
10	Bolt	Steel, Cold forge	6	0.072	0.32	0.06%
05	Intake Rocker Arm Module			3.178	106.85	20.68%
4	Intake Rocker Arm	4140 Steel, Sand-Casting	6	1.302	16.50	3.19%
5	Pushrod	S-Steel-304, Machining	6	0.528	26.80	5.19%
6	Housing	8620 Steel, Machining	6	0.925	23.86	4.62%
7	Swivel Rod	E52100 Steel, Machining	6	0.129	13.68	2.65%
8	Bearing-1	E52100 Steel, Machining	6	0.144	12.99	2.51%
9	Bearing-2	E52100 Steel, Machining	6	0.078	12.69	2.46%
10	Bolt	Steel, Cold forge	6	0.072	0.32	0.06%
08	Cam Shaft			18.050	130.43	25.24%
11	Cam_Shaft	Steel, Machining	1	14.000	104.28	20.18%
12	Cam gear	8620 Steel, Forging	1	3.900	18.68	3.62%
12	Camshaft Sensing	Powder Metal	1	0.150	7.47	1.45%
09	Other Valvetrain Modules			7.516	137.25	26.56%
12	Intake Valve	Steel, Forging	12	0.495	26.18	5.07%
12	Exhaust Valve	Steel, Forging	12	0.486	29.86	5.78%
12	Valve cover	PA66, Injection Molding	1	4.825	40.86	7.91%
12	Valve spring	Steel, Coiling	24	0.972	29.05	5.62%
12	Retainers, Cotters, Seats	NA	24	0.738	11.30	2.19%
10	Assembly			0.000	22.26	4.31%
A	Assembly of all Components	Assembly	1	0.000	22.26	4.31%
Total Cost				32.44	516.70	100%

4. CYLINDER DEACTIVATION MODULE ANALYSIS

Unlike the baseline valvetrain teardown, CDA valvetrain is evaluated based on disassembled modules and part drawings. Module breakdown sequence is kept similar to the Baseline valvetrain to aid in the cost and design comparison study. **Table 4-1** provides a list of modules included in this analysis, along with subsystem key attributes and manufacturing cost breakdown.

Table 4-1: CDA Valvetrain Attribute and Cost Summary Overview

System:	Engine		
Subsystem:	Valvetrain		
Sub-Subsystem Categorization with Subsystem			
1	Exhaust Bridge Module	Included in Analysis	
2	Intake Bridge Module	Included in Analysis	
3	Exhaust Rocker Arm Module	Included in Analysis	
4	Brake Rocker Arm Module	Included in Analysis	
5	Intake Rocker Arm Module	Included in Analysis	
6	Oil Control Module	Included in Analysis	
7	Rocker Shaft	Included in Analysis	
8	Cam Shaft	Included in Analysis	
9	Intake Valve	Not Included in Analysis	
	Exhaust Valve	Not Included in Analysis	
	Valve cover	Not Included in Analysis	
	Valve spring	Not Included in Analysis	
	Spring Retainers, Cotters, Spring Seats	Not Included in Analysis	
	Harness	Included in Analysis	
10	Assembly of Entire Subsystem	Included in Analysis	
Key Attributes			
1	Components that are different from baseline - Rocker arms, Exhaust bridge, rocker shaft and Oil Control Module		
2	Engine braking is achieved through gear mechanism as opposed to Spring lock mechanism in Baseline valvetrain		
3	In addition to Oil Control Module for Engine Braking, CDA requires an Oil Control Valve per cylinder for cylinder deactivation		
4	Rocker shaft has more holes to accommodate additions oil control valves		
5	Exhaust bridge is mounted on cylinder head through a post		
6	Requires additional machining on cylinder head		
Cost Structure			
Material	$ 340.77	EIS	$ 4.06
Labor	$ 55.08	SG&A	$ 52.84
Burden	$ 386.57	Profit	$ 48.78
TDMC	$ 782.42	ED&T	$ 18.10
		TIMC	$ 123.78
TMC	**$ 906.20**	**Subsystem Mass (kg)**	**65.39**

TDMC - Total Direct Manufacturing Cost, EIS - End Item Scrap, SG&A - Selling, General & Administrative costs, ED&T - Engineering, Design & Testing, TIMC - Total Indirect Manufacturing Cost, TMC - Total manufacturing Cost

The Cost Model Analysis Templates (CMAT) for the valvetrain subsystem shown in **Table 4-2**, provides cost breakdowns for key components evaluated for CDA installed in all 6 cylinders for a 15L I6 engine type III valvetrain. The module classification is developed similar to the baseline classification.

Table 4-2: 15L Engine Valvetrain w/ CDA Cost Summary Sheet

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Total Mass	Mass Total Percent "%"	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain				kg	%	US $	%
01	Exhaust Bridge Module		6	1.580	2.42%	25.76	2.84%
1	Pin_Exhaust_Bridge	8620 Steel, Machining	6	0.162	0.25%	5.85	0.65%
2	Exhaust_Bridge	8620 Steel, Forging	6	1.033	1.58%	11.15	1.23%
3	Post	E52100 Steel, Machining	6	0.384	0.59%	8.31	0.92%
3	Clip	Alloy Steel, Stamping	6	0.001	0.00%	0.46	0.05%
02	Intake Bridge Module		6	0.722	1.10%	8.36	0.92%
4	Intake_Bridge	8620 Steel, Forging	6	0.722	1.10%	8.36	0.92%
03	Exhaust Rocker Arm Module		6	6.870	10.51%	120.14	13.26%
5	Shaft_Cam_Roller	P5 Steel, Machining	6	0.281	0.43%	12.85	1.42%
6	Cam_Roller	E52100 Steel, Machining	6	0.482	0.74%	11.00	1.21%
7	Center_Sleeve	4140 Steel, Stamping	6	0.107	0.16%	2.24	0.25%
8	Nut_Resting_Assembly	Steel, Cold forge	6	0.120	0.18%	2.74	0.30%
9	Snap_Ring_Internal	Alloy Steel, Stamping	6	0.005	0.01%	1.92	0.21%
10	Plate_Spring_Cover	16MnCr5, Stamping	6	0.027	0.04%	0.71	0.08%
11	Small_Spring	Steel, Coiling	6	0.029	0.04%	2.34	0.26%
12	Large_Spring	Steel, Coiling	6	0.054	0.08%	2.40	0.27%
13	Locking_Dowels	A2 Steel, Machining	12	0.024	0.04%	4.46	0.49%
14	Spring_Dowels	Steel, Coiling	6	0.001	0.00%	1.53	0.17%
15	Resting_Joint	E52100 Steel, Machining	6	0.056	0.09%	4.53	0.50%
16	Snap_Ring	Steel, Stamping	6	0.004	0.01%	0.47	0.05%
17	Mount_Resting_Joint	Powder Metal	6	0.107	0.16%	3.20	0.35%
18	Internal_Resting_Housing	16Mn5Cr, Machining	6	0.213	0.33%	9.30	1.03%
19	Resting_Housing	8620 Steel, Machining	6	0.368	0.56%	11.39	1.26%
20	Exhaust_Rocker_Arm	4140 Steel, Forging	6	4.990	7.63%	49.08	5.42%
04	Brake Rocker Arm Module		6	5.416	8.28%	80.43	8.88%
5	Shaft_Cam_Roller	P5 Steel, Machining	6	0.281	0.43%	12.85	1.42%
7	Center_Sleeve	4140 Steel, Stamping	6	0.107	0.16%	2.24	0.25%
21	Brake_Cam_Roller	E52100 Steel, Machining	6	0.590	0.90%	9.59	1.06%
22	Bolt_Sleeve	Alloy Steel, Machining	6	0.056	0.09%	3.14	0.35%
23	Resting_Bolt	Steel, Cold Forge	6	0.098	0.15%	0.34	0.04%
24	Key_Gear	Powder Metal	6	0.104	0.16%	5.53	0.61%
25	Internal_Spring	Steel, Coiling	6	0.020	0.03%	2.74	0.30%

26	Internal_Gear_Sleeve	Powder Metal	6	0.087	0.13%	3.25	0.36%
27	Snap_Ring_Side	Alloy Steel, Stamping	6	0.001	0.00%	0.46	0.05%
28	Washer_Spring	Alloy Steel, Stamping	6	0.001	0.00%	0.46	0.05%
29	Spring_Alignment_Rod	Steel, Coiling	6	0.020	0.03%	2.66	0.29%
30	Alignment_Rod	E52100 Steel, Machining	6	0.029	0.04%	2.45	0.27%
31	Cap_Side	Alloy Steel, Stamping	6	0.004	0.01%	0.47	0.05%
32	Misc_Bolt	Steel, Cold forge	6	0.001	0.00%	0.34	0.04%
33	Misc_Snap_Ring	Alloy Steel, Stamping	6	0.001	0.00%	0.46	0.05%
34	Brake_Rocker_Arm	4140 Steel, Forging	6	4.012	6.14%	33.46	3.69%
05	Intake Rocker Arm Module		6	7.892	12.07%	128.51	14.18%
5	Shaft_Cam_Roller	P5 Steel, Machining	6	0.281	0.43%	12.85	1.42%
6	Cam_Roller	E52100 Steel, Machining	6	0.482	0.74%	11.00	1.21%
7	Center_Sleeve	4140 Steel, Stamping	6	0.107	0.16%	2.24	0.25%
8	Nut_Resting_Assembly	Steel, Cold forge	6	0.120	0.18%	2.74	0.30%
9	Snap_Ring_Internal	Alloy Steel, Stamping	6	0.005	0.01%	1.92	0.21%
10	Plate_Spring_Cover	16MnCr5, Stamping	6	0.027	0.04%	0.71	0.08%
11	Small_Spring	Steel, Coiling	6	0.029	0.04%	2.34	0.26%
12	Large_Spring	Steel, Coiling	6	0.054	0.08%	2.40	0.27%
13	Locking_Dowels	A2 Steel, Machining	12	0.024	0.04%	4.46	0.49%
14	Spring_Dowels	Steel, Coiling	6	0.001	0.00%	1.53	0.17%
15	Resting_Joint	E52100 Steel, Machining	6	0.056	0.09%	4.53	0.50%
16	Snap_Ring	Steel, Stamping	6	0.004	0.01%	0.47	0.05%
17	Mount_Resting_Joint	Powder Metal	6	0.107	0.16%	3.20	0.35%
18	Internal_Resting_Housing	16Mn5Cr, Machining	6	0.213	0.33%	9.30	1.03%
19	Resting_Housing	8620 Steel, Machining	6	0.368	0.56%	11.39	1.26%
35	Intake_Rocker_Arm	4140 Steel, Forging	6	6.013	9.19%	57.45	6.34%
06	Oil Control Module			5.296	8.10%	112.87	12.46%
36	Brake Oil Control Valve	-----	2	0.346	0.53%	11.83	1.31%
37	OCV Mounting	1040 Steel, Sand-casting	4	3.912	5.98%	31.01	3.42%
37	CDA Oil Control Valve	-----	6	1.038	1.59%	70.03	7.73%
07	Rocker Shaft		2	6.044	9.24%	70.18	7.74%
38	Rocker_Arm_Rod	4140 Steel, Machining	2	6.044	9.24%	70.18	7.74%
08	Cam Shaft		1	21.100	32.27%	144.86	15.99%
39	Cam_Shaft	Steel, Machining	1	17.000	26.00%	109.99	12.14%
40	Cam gear	8620 Steel, Forging	1	3.900	5.96%	24.91	2.75%
40	Camshaft Sensing	Powder Metal	1	0.200	0.31%	9.96	1.10%
09	Other Valvetrain Modules			10.472	16.01%	189.96	20.96%
40	Intake Valve	Steel, Forging	12	0.660	1.01%	34.91	3.85%
40	Exhaust Valve	Steel, Forging	12	0.648	0.99%	39.81	4.39%
40	Valve cover	PA66, Injection Molding	1	6.434	9.84%	54.48	6.01%
40	Valve spring	Steel, Coiling	24	1.296	1.98%	38.74	4.27%
40	Retainers, Cotters, Seats	NA	24	0.984	1.50%	15.06	1.66%
40	Harness	-----	1	0.450	0.69%	6.96	0.77%

10	Assembly			0.000	0.00%	25.13	2.77%
A	Assembly of all Components	Assembly	1	0.000	0.00%	25.13	2.77%
	Total Cost			65.39	100%	906.20	100%

The Cost Model Analysis Templates (CMAT) for the valvetrain subsystem shown in **Table 4-3**, provides cost breakdowns for key components evaluated for CDA installed in all 6 cylinders for a 9L I6 engine type V valvetrain. Though Cummins L9 valvetrain is taken as reference for this analysis, the same cost is applicable to Cummins B6.7 valvetrain as they share same valvetrain components. In appendix, **Figure 8-6** provides a comparison of Exhaust rocker arm components in Baseline vs CDA valvetrain. Components with same color scheme depict similar functionality.

Table 4-3: 9L Engine type V Valvetrain w/ CDA Cost Summary Sheet

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Total Mass	Mass Total Percent "%"	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain				kg	%	US $	%
01	Exhaust Bridge Module		6	0.300	0.89%	6.80	1.02%
1	Exhaust Bridge	8620 Steel, Forging	6	0.300	0.89%	6.80	1.02%
02	Intake bridge Module			0.300	0.89%	6.80	1.02%
2	Intake Bridge	8620 Steel, Forging	6	0.300	0.89%	6.80	1.02%
03	Exhaust Rocker Arm Module			3.454	10.23%	127.92	19.10%
3	Exhaust Rocker Arm	4140 Steel, Sand-Casting	6	1.218	3.61%	30.24	4.51%
5	Pushrod	S-Steel-304, Machining	6	0.528	1.56%	26.80	4.00%
6	Outer body	8620 Steel, Machining	6	0.684	2.03%	21.66	3.23%
7	Inner body	8620 Steel, Machining	6	0.330	0.98%	8.76	1.31%
8	Latch pin	A2 Steel, Machining	12	0.024	0.07%	3.45	0.51%
9	Latch spring	Steel, Coiling	6	0.001	0.00%	1.33	0.20%
10	Socket	E52100 Steel, Machining	6	0.046	0.14%	3.63	0.54%
11	Axle	E52100 Steel, Machining	6	0.114	0.34%	13.62	2.03%
12	Axle clip	Steel, Stamping	6	0.004	0.01%	0.47	0.07%
13	Roller bearing	E52100 Steel, Machining	6	0.194	0.57%	13.38	2.00%
14	Motion spring	Steel, Coiling	6	0.078	0.23%	1.81	0.27%
15	Retainer	Steel, Stamping	6	0.078	0.23%	0.80	0.12%
16	Clip	Steel, Stamping	6	0.001	0.00%	0.46	0.07%
17	Washer	Steel, Stamping	6	0.002	0.01%	0.46	0.07%
18	Shim	Steel, Stamping	6	0.080	0.24%	0.76	0.11%
3	Bolt	Steel, Cold forge	6	0.072	0.21%	0.32	0.05%
05	Intake Rocker Arm Module			3.538	10.48%	128.46	19.18%
4	Intake Rocker Arm	4140 Steel, Sand-Casting	6	1.302	3.86%	30.77	4.59%
5	Pushrod	S-Steel-304, Machining	6	0.528	1.56%	26.80	4.00%
6	Outer body	8620 Steel, Machining	6	0.684	2.03%	21.66	3.23%

7	Inner body	8620 Steel, Machining	6	0.330	0.98%	8.76	1.31%
8	Latch pin	A2 Steel, Machining	12	0.024	0.07%	3.45	0.51%
9	Latch spring	Steel, Coiling	6	0.001	0.00%	1.33	0.20%
10	Socket	E52100 Steel, Machining	6	0.046	0.14%	3.63	0.54%
11	Axle	E52100 Steel, Machining	6	0.114	0.34%	13.62	2.03%
12	Axle clip	Steel, Stamping	6	0.004	0.01%	0.47	0.07%
13	Roller bearing	E52100 Steel, Machining	6	0.194	0.57%	13.38	2.00%
14	Motion spring	Steel, Coiling	6	0.078	0.23%	1.81	0.27%
15	Retainer	Steel, Stamping	6	0.078	0.23%	0.80	0.12%
16	Clip	Steel, Stamping	6	0.001	0.00%	0.46	0.07%
17	Washer	Steel, Stamping	6	0.002	0.01%	0.46	0.07%
18	Shim	Steel, Stamping	6	0.080	0.24%	0.76	0.11%
3	Bolt	Steel, Cold forge	6	0.072	0.21%	0.32	0.05%
06	Oil Control Module			3.972	11.77%	108.05	16.13%
19	OCV Mounting	1040 Steel, Sand-casting	1	2.934	8.69%	23.24	3.47%
20	CDA Oil Control Valve	-----	6	1.038	3.07%	67.81	10.12%
21	Block Machining	Machining	1	0.000	0.00%	17.00	2.54%
08	Cam Shaft		1	14.578	43.18%	130.43	19.47%
22	Cam_Shaft	Steel, Machining	1	14.000	41.47%	104.28	15.57%
23	Cam gear	8620 Steel, Forging	1	0.428	1.27%	18.68	2.79%
23	Camshaft Sensing	Powder Metal	1	0.150	0.44%	7.47	1.12%
09	Other Valvetrain Modules			7.616	22.56%	138.74	20.71%
23	Intake Valve	Steel, Forging	12	0.495	1.47%	26.18	3.91%
23	Exhaust Valve	Steel, Forging	12	0.486	1.44%	29.86	4.46%
23	Valve cover	PA66, Injection Molding	1	4.825	14.29%	40.86	6.10%
23	Valve spring	Steel, Coiling	24	0.972	2.88%	29.05	4.34%
23	Retainers, Cotters, Seats	NA	24	0.738	2.19%	11.30	1.69%
23	Harness	Powder Metal	1	0.100	0.30%	1.49	0.22%
10	Assembly			0.000	0.00%	22.62	3.38%
A	Assembly of all Components	Assembly	1	0.000	0.00%	22.62	3.38%
Total Cost				33.76	100%	669.83	100%

5. FLEXVALVE LIVC MODULE ANALYSIS

Unlike the baseline valvetrain teardown, FlexValve LIVC valvetrain is evaluated based on part drawings. Module breakdown sequence is kept similar to the Baseline valvetrain to aid in the cost and design comparison study. **Table 5-1** provides a list of modules included in this analysis, along with subsystem key attributes and manufacturing cost breakdown.

Table 5-1: LIVC Valvetrain Attribute and Cost Summary Overview

System:	Engine		
Subsystem:	Valvetrain		
Sub-Subsystem Categorization with Subsystem			
1	Exhaust Bridge Module	Included in Analysis	
2	Intake Bridge Module	Included in Analysis	
3	Exhaust Rocker Arm Module	Included in Analysis	
4	Brake Rocker Arm Module	Included in Analysis	
5	Intake Rocker Arm Module	Included in Analysis	
6	Oil Control Module	Included in Analysis	
7	Rocker Shaft	Included in Analysis	
8	Cam Shaft	Included in Analysis	
9	Intake Valve	Not Included in Analysis	
	Exhaust Valve	Not Included in Analysis	
	Valve cover	Not Included in Analysis	
	Valve spring	Not Included in Analysis	
	Spring Retainers, Cotters, Spring Seats	Not Included in Analysis	
	Harness	Included in Analysis	
10	Assembly of Entire Subsystem	Included in Analysis	
Key Attributes			
1	Components that are different from baseline - Intake Rocker Arm, Camshaft, Cam gear and Camshaft Sensing Hardware		
2	Change in Rocker shaft position resulted in minor changes to Exhaust bridge and Exhaust Rocker Arm modules		
3	FlexValve rocker consists of two rocker arms to achieve Late Intake Valve Closing. A moving cam lobe on camshaft is used to vary the intake valve lift		
4	LIVC has an assembled camshaft design compared to baseline (machined). It includes Fixed lobes, moving lobes, Driveshaft, Pin, bearing elements and FlexValve actuator to facilitate Late Intake Valve Closing mechanism		
Cost Structure			
Material	$ 290.90	EIS	$ 4.43
Labor	$ 122.05	SG&A	$ 57.68
Burden	$ 415.37	Profit	$ 53.16
TDMC	$ 828.32	ED&T	$ 21.15
		TIMC	$ 136.42
TMC	**$ 964.74**	**Subsystem Mass (kg)**	**71.16**
TDMC - Total Direct Manufacturing Cost, EIS - End Item Scrap, SG&A - Selling, General & Administrative costs, ED&T - Engineering, Design & Testing, TIMC - Total Indirect Manufacturing Cost, TMC - Total manufacturing Cost			

The Cost Model Analysis Templates (CMAT) for the Valvetrain Subsystem shown in **Table 5-2**, provides cost breakdowns for key components evaluated for LIVC installed (in all 6 cylinders) of a 15L I6 engine Type III valvetrain. The module classification is developed similar to the baseline classification.

Table 5-2: 15L Engine Valvetrain w/ LIVC Cost Summary Sheet

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Total Mass	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain				kg	US $	%
01	Exhaust Bridge Module			1.046	15.42	1.60%
1	Pin_Exhaust_Bridge	8620 Steel, Machining	6	0.162	5.62	0.58%
2	Exhaust_Bridge	8620 Steel, Forging	6	0.884	9.80	1.02%
02	Intake Bridge Module			0.869	8.66	0.90%
4	Intake_Bridge	8620 Steel, Forging	6	0.869	8.66	0.90%
03	Exhaust Rocker Arm Module			5.191	71.69	7.43%
5	Nut_Resting_Joint	Steel, Cold forge	6	0.056	0.80	0.08%
6	Resting_Joint	E52100 Steel, Machining	6	0.226	10.04	1.04%
7	Shaft_Cam_Roller	P5 Steel, Machining	6	0.281	12.85	1.33%
8	Cam_Roller	E52100 Steel, Machining	6	0.482	11.00	1.14%
9	Exhaust_Center_Sleeve	4140 Steel, Stamping	6	0.107	2.24	0.23%
10	Exhaust_Rocker_Arm	Ductile-iron, Sand-casting	6	4.038	34.77	3.60%
04	Brake Rocker Arm Module			7.711	91.41	9.48%
11	Brake_Nut_Resting_Nut	Steel, Cold forge	6	0.028	1.19	0.12%
12	Brake_Resting_Assembly	E52100 Steel, Machining	6	0.385	9.87	1.02%
13	Snap_ring_Oil_Flow	Alloy Steel, Stamping	6	0.007	1.94	0.20%
14	Cap_Oil_Flow	Alloy Steel, Stamping	6	0.035	2.07	0.21%
15	Spring_Oil_Flow	Steel, Coiling	6	0.010	0.54	0.06%
16	Oil_Flow_Assembly	E52100 Steel, Machining & Assy	6	0.140	9.03	0.94%
17	Brake_Shaft_Cam_Roller	Bronze, Machining	6	0.437	11.15	1.16%
18	Brake_Cam_Roller	E52100 Steel, Machining	6	0.482	11.15	1.16%
19	Brake_Center_Sleeve	4140 Steel, Stamping	6	0.150	2.38	0.25%
20	Brake_Rocker_Arm	Ductile-iron, Sand-Casting	6	6.036	42.09	4.36%
05	Intake Rocker Arm Module			12.733	160.88	16.68%
21	FlexValve_Rocker_Arm	4140 Steel, Sand-Casting	6	4.806	44.15	4.58%
22	Output_Rocker_Arm	4140 Steel, Sand-Casting	6	3.060	31.70	3.29%
23	Spring_Control	Steel, Coiling	6	0.048	0.49	0.05%
24	Seat_Control_Spring	8620 Steel, Machining	6	0.209	2.69	0.28%
25	Intake_Roller_Axle_Moving	Bronze, Machining	6	0.384	10.24	1.06%
26	Cam_Roller_Moving	E52100 Steel, Machining	6	0.426	10.44	1.08%
27	Intake_Roller_Axle_Fixed	Bronze, Machining	6	0.600	14.74	1.53%
28	Cam_Roller_Fixed	E52100 Steel, Machining	12	0.678	15.27	1.58%

29	Pivot_Axle	E52100 Steel, Machining	6	1.380	11.34	1.17%
30	FlexValve_Rocker_Center_Sleeve	4140 Steel, Stamping	12	0.300	2.64	0.27%
31	Output_Rocker_Center_Sleeve	4140 Steel, Stamping	6	0.240	1.58	0.16%
32	Grub Screw	Steel, Machining	24	0.048	0.90	0.09%
33	Intake_Resting_Joint_Foot	Foot / Cap of the Joint	6	0.054	4.49	0.47%
34	Intake_Resting_Joint_Shaft	E52100 Steel, Machining	6	0.118	5.55	0.58%
35	Intake_Nut_Resting_Joint	Steel, Cold forge	6	0.028	1.19	0.12%
36	Retaining Plate - Roller	4140 Steel, Stamping	12	0.300	1.68	0.17%
36	Countersunk Torx Screw	Steel, Cold forge	12	0.054	1.78	0.18%
06	Oil Control Module			1.064	20.77	2.15%
37	Bolt_Oil_Control	Steel, Cold forge	2	0.009	0.33	0.03%
38	Oring_Oil_Control	Rubber, Injection Molding	2	0.001	0.01	0.00%
39	Small_Oring_Oil_Control	Rubber, Injection Molding	2	0.000	0.01	0.00%
40	Filter_Oil_Control	Overmolded filter	2	0.001	1.15	0.12%
41	Oil_Control_Cover	Plastic, Injection Molding	2	0.008	1.08	0.11%
42	Cap_Oil_Control	Alloy Steel, Stamping	2	0.046	0.77	0.08%
43	Oil_Control_Internals_Cover	Commodity	2	0.109	3.27	0.34%
44	Dowel_Oil_Control	Stainless Steel, Machining	2	0.020	1.32	0.14%
45	Pin_Holder_Plate	Powder Metal	2	0.037	0.59	0.06%
46	Pin_oil_Control	Alloy Steel, Machining	2	0.001	0.14	0.01%
47	Bracket_Oil_Filter	Alloy Steel, Blanking	2	0.029	0.72	0.07%
48	Internal_Pin	Alloy Steel, Machining	2	0.005	0.70	0.07%
49	Sleeve_Internal_Pin	Alloy Steel, Machining	2	0.002	0.66	0.07%
50	Housing_Internal_pin	Al, Die-cast	2	0.079	1.09	0.11%
51	Mounting_Oil_Control	Powder Metal	2	0.718	8.94	0.93%
07	Rocker Shaft			6.044	68.52	7.10%
52	Rocker_Arm_Rod	4140 Steel, Machining	2	6.044	68.52	7.10%
08	Cam Shaft			26.285	319.30	33.10%
53	Cam Lobe, Fixed, Intake	E52100 (100Cr6) Steel/Forged	12	2.040	46.58	4.83%
54	Cam Lobe, Movable, Intake	E52100 (100Cr6) Steel/Forged	6	0.984	30.51	3.16%
55	Cam Lobe, Fixed, Exhaust	E52100 (100Cr6) Steel/Forged	6	0.936	25.17	2.61%
56	Cam Lobe, Fixed, Exhaust Brake	E52100 (100Cr6) Steel/Forged	6	1.458	31.23	3.24%
57	Core Plug, DIN 443 - 26.5 - B - St	DC03-A EN10130//Pur item	1	0.011	0.12	0.01%
58	Camshaft Tube, Machined	34MnB5 +C (cold drawn)/Machine	1	4.094	18.40	1.91%
59	Driveshaft	4340 Steel/Friction Welding & Machine	1	3.933	19.84	2.06%
60	Driver Pin	ST Typ A ISO 8734	6	0.936	1.34	0.14%
61	Bearing Element	42CrMo4+QT EN10083-3/Pur item	6	3.684	50.19	5.20%
62	Front Bearing Element	42CrMo4+QT EN10083-3/Pur item	1	0.667	10.20	1.06%
D	Cam Gear	16MnCr5 / Forged	1	4.094	29.85	3.09%
F	FlexValve Actuator	Multi part assy	1	3.448	55.88	5.79%
09	Other Valvetrain Modules			10.222	184.57	19.13%
O	Intake Valve	Steel, Forging	12	0.660	34.91	3.62%

O	Exhaust Valve	Steel, Forging	12	0.648	39.81	4.13%
O	Valve cover	PA66, Injection Molding	1	6.434	54.48	5.65%
O	Valve spring	Steel, Coiling	24	1.296	38.74	4.02%
O	Retainers, Cotters, Seats	NA	24	0.984	15.06	1.56%
O	Harness	-----	1	0.200	1.57	0.16%
10	Assembly			0.000	23.51	2.44%
A	Assembly of all Components	Assembly	1	0.000	23.51	2.44%
Total Cost				71.16	964.74	100%

FlexValve LIVC Design is not directly applicable to type V valvetrains due to less package space available within the cylinder head.

The X15 camshaft is a feed through design. This requires additional camshaft bearing components that are shrunk onto the camshaft tube. For most applications in this engine category these components would not be required, and the camshaft would be supported directly on the tube. **Table 5-3** provides cost summary for a typical 15L engine valvetrain eliminating the need for camshaft bearing components.

Table 5-3: 15L Engine Valvetrain w/ LIVC Cost Summary sheet (other SOHC engines)

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Total Mass	Total Mfg Cost (TMC)	Total Mfg Cost (%)
Valvetrain				kg	US $	%
01	Exhaust Bridge Module			1.046	15.42	1.71%
1	Pin_Exhaust_Bridge	8620 Steel, Machining	6	0.162	5.62	0.62%
2	Exhaust_Bridge	8620 Steel, Forging	6	0.884	9.80	1.09%
02	Intake Bridge Module			0.869	8.66	0.96%
4	Intake_Bridge	8620 Steel, Forging	6	0.869	8.66	0.96%
03	Exhaust Rocker Arm Module			5.191	73.95	8.19%
5	Nut_Resting_Joint	Steel, Cold forge	6	0.056	0.80	0.09%
6	Resting_Joint	E52100 Steel, Machining	6	0.226	10.04	1.11%
7	Shaft_Cam_Roller	P5 Steel, Machining	6	0.281	12.85	1.42%
8	Cam_Roller	E52100 Steel, Machining	6	0.482	11.00	1.22%
9	Exhaust_Center_Sleeve	4140 Steel, Stamping	6	0.107	2.24	0.25%
10	Exhaust_Rocker_Arm	4140 Steel, Sand-Casting	6	4.038	37.03	4.10%
04	Brake Rocker Arm Module			7.711	90.78	10.06%
11	Brake_Nut_Resting_Nut	Steel, Cold forge	6	0.028	1.19	0.13%
12	Brake_Resting_Assembly	E52100 Steel, Machining	6	0.385	9.87	1.09%
13	Snap_ring_Oil_Flow	Alloy Steel, Stamping	6	0.007	1.94	0.22%
14	Cap_Oil_Flow	Alloy Steel, Stamping	6	0.035	2.07	0.23%
15	Spring_Oil_Flow	Steel, Coiling	6	0.010	0.54	0.06%
16	Oil_Flow_Assembly	E52100 Steel, Machining & Assy	6	0.140	9.03	1.00%
17	Brake_Shaft_Cam_Roller	Bronze, Machining	6	0.437	11.15	1.24%

18	Brake_Cam_Roller	E52100 Steel, Machining	6	0.482	11.15	1.24%
19	Brake_Center_Sleeve	4140 Steel, Stamping	6	0.150	2.38	0.26%
20	Brake_Rocker_Arm	Gray Iron, Sand-Casting	6	6.036	41.46	4.59%
05	Intake Rocker Arm Module			12.733	160.88	17.83%
21	FlexValve_Rocker_Arm	4140 Steel, Sand-Casting	6	4.806	44.15	4.89%
22	Output_Rocker_Arm	4140 Steel, Sand-Casting	6	3.060	31.70	3.51%
23	Spring_Control	Steel, Coiling	6	0.048	0.49	0.05%
24	Seat_Control_Spring	8620 Steel, Machining	6	0.209	2.69	0.30%
25	Intake_Roller_Axle_Moving	Bronze, Machining	6	0.384	10.24	1.13%
26	Cam_Roller_Moving	E52100 Steel, Machining	6	0.426	10.44	1.16%
27	Intake_Roller_Axle_Fixed	Bronze, Machining	6	0.600	14.74	1.63%
28	Cam_Roller_Fixed	E52100 Steel, Machining	12	0.678	15.27	1.69%
29	Pivot_Axle	E52100 Steel, Machining	6	1.380	11.34	1.26%
30	FlexValve_Rocker_Center_Sleeve	4140 Steel, Stamping	12	0.300	2.64	0.29%
31	Output_Rocker_Center_Sleeve	4140 Steel, Stamping	6	0.240	1.58	0.18%
32	Grub Screw	Steel, Machining	24	0.048	0.90	0.10%
33	Intake_Resting_Joint_Foot	Foot / Cap of the Joint	6	0.054	4.49	0.50%
34	Intake_Resting_Joint_Shaft	E52100 Steel, Machining	6	0.118	5.55	0.62%
35	Intake_Nut_Resting_Joint	Steel, Cold forge	6	0.028	1.19	0.13%
36	Retaining Plate - Roller	4140 Steel, Stamping	12	0.300	1.68	0.19%
36	Countersunk Torx Screw	Steel, Cold forge	12	0.054	1.78	0.20%
06	Oil Control Module			1.064	20.77	2.30%
37	Bolt_Oil_Control	Steel, Cold forge	2	0.009	0.33	0.04%
38	Oring_Oil_Control	Rubber, Injection Molding	2	0.001	0.01	0.00%
39	Small_Oring_Oil_Control	Rubber, Injection Molding	2	0.000	0.01	0.00%
40	Filter_Oil_Control	Overmolded filter	2	0.001	1.15	0.13%
41	Oil_Control_Cover	Plastic, Injection Molding	2	0.008	1.08	0.12%
42	Cap_Oil_Control	Alloy Steel, Stamping	2	0.046	0.77	0.09%
43	Oil_Control_Internals_Cover	Commodity	2	0.109	3.27	0.36%
44	Dowel_Oil_Control	Stainless Steel, Machining	2	0.020	1.32	0.15%
45	Pin_Holder_Plate	Powder Metal	2	0.037	0.59	0.06%
46	Pin_oil_Control	Alloy Steel, Machining	2	0.001	0.14	0.02%
47	Bracket_Oil_Filter	Alloy Steel, Blanking	2	0.029	0.72	0.08%
48	Internal_Pin	Alloy Steel, Machining	2	0.005	0.70	0.08%
49	Sleeve_Internal_Pin	Alloy Steel, Machining	2	0.002	0.66	0.07%
50	Housing_Internal_pin	Al, Die-cast	2	0.079	1.09	0.12%
51	Mounting_Oil_Control	Powder Metal	2	0.718	8.94	0.99%
07	Rocker Shaft			6.044	64.96	7.20%
52	Rocker_Arm_Rod	4140 Steel, Machining	2	6.044	64.96	7.20%
08	Cam Shaft			21.934	258.91	28.69%
53	Cam Lobe, Fixed, Intake	E52100 (100Cr6) Steel/Forged	12	2.040	46.58	5.16%
54	Cam Lobe, Movable, Intake	E52100 (100Cr6) Steel/Forged	6	0.984	30.51	3.38%
55	Cam Lobe, Fixed, Exhaust	E52100 (100Cr6) Steel/Forged	6	0.936	25.17	2.79%

56	Cam Lobe, Fixed, Exhaust Brake	E52100 (100Cr6) Steel/Forged	6	1.458	31.23	3.46%
57	Core Plug, DIN 443 - 26.5 - B - St	DC03-A EN10130//Pur item	1	0.011	0.12	0.01%
58	Camshaft Tube, Machined	34MnB5 +C (cold drawn)/Machine	1	4.094	18.40	2.04%
59	Driveshaft	4340 Steel/Friction Welding & Machine	1	3.933	19.84	2.20%
60	Driver Pin	ST Typ A ISO 8734	6	0.936	1.34	0.15%
61	Bearing Element	Not required as camshaft would be supported directly on the tube				
62	Front Bearing Element					
D	Cam Gear	16MnCr5 / Forged	1	4.094	29.85	3.31%
F	FlexValve Actuator	Multi part assy	1	3.448	55.88	6.19%
09	Other Valvetrain Modules			10.222	184.57	20.45%
O	Intake Valve	Steel, Forging	12	0.660	34.91	3.87%
O	Exhaust Valve	Steel, Forging	12	0.648	39.81	4.41%
O	Valve cover	PA66, Injection Molding	1	6.434	54.48	6.04%
O	Valve spring	Steel, Coiling	24	1.296	38.74	4.29%
O	Retainers, Cotters, Seats	NA	24	0.984	15.06	1.67%
O	Harness	-----	1	0.200	1.57	0.17%
10	Assembly			0.000	23.51	2.61%
A	Assembly of all Components	Assembly	1	0.000	23.51	2.61%
Total Cost				66.81	902.41	100%

6. BASELINE VS CDA VS LIVC – DESIGN AND COST COMPARISON

This section provides a detailed design and manufacturing attribute comparison between the evaluated valvetrain technologies. **Table 6-1** shows BOM comparison for all 3 valvetrain technologies.

Table 6-1: BOM Comparison for 15L Engine (Baseline vs CDA vs LIVC)

Modules	Baseline	CDA	LIVC
Exhaust Bridge Module	Pin_Exhaust_Bridge Exhaust_Bridge	Pin_Exhaust_Bridge Exhaust_Bridge Post Clip	Pin_Exhaust_Bridge Exhaust_Bridge
Intake Bridge Module	Intake_Bridge	Intake_Bridge	Intake_Bridge
Exhaust Rocker Arm Module	Nut_Resting_Joint Resting_Joint Shaft_Cam_Roller Cam_Roller Exhaust_Center_Sleeve Exhaust_Rocker_Arm	Shaft_Cam_Roller Cam_Roller Center_Sleeve Nut_Resting_Assembly Snap_Ring_Internal Plate_Spring_Cover Small_Spring Large_Spring Locking_Dowels Spring_Dowels Resting_Joint Snap_Ring Mount_Resting_Joint Internal_Resting_Housing Resting_Housing Exhaust_Rocker_Arm	Nut_Resting_Joint Resting_Joint Shaft_Cam_Roller Cam_Roller Exhaust_Center_Sleeve Exhaust_Rocker_Arm
Brake Rocker Arm Module	Brake_Nut_Resting_Nut Brake_Resting_Assembly Snap_ring_Oil_Flow Cap_Oil_Flow Spring_Oil_Flow Oil_Flow_Assembly Brake_Shaft_Cam_Roller Brake_Cam_Roller Brake_Center_Sleeve Brake_Rocker_Arm	Shaft_Cam_Roller Center_Sleeve Brake_Cam_Roller Bolt_Sleeve Resting_Bolt Key_Gear Internal_Spring Internal_Gear_Sleeve Snap_Ring_Side Washer_Spring Spring_Alignment_Rod Alignment_Rod Cap_Side Misc_Bolt Misc_Snap_Ring	Brake_Nut_Resting_Nut Brake_Resting_Assembly Snap_ring_Oil_Flow Cap_Oil_Flow Spring_Oil_Flow Oil_Flow_Assembly Brake_Shaft_Cam_Roller Brake_Cam_Roller Brake_Center_Sleeve Brake_Rocker_Arm

		Brake_Rocker_Arm	
Intake Rocker Arm Module	Intake_Nut_Resting_Joint Intake_Resting_Joint Intake_Shaft_Cam_Roller Intake_Roller_Arm Intake_Center_Sleeve Intake_Rocker_Arm	Shaft_Cam_Roller Cam_Roller Center_Sleeve Nut_Resting_Assembly Snap_Ring_Internal Plate_Spring_Cover Small_Spring Large_Spring Locking_Dowels Spring_Dowels Resting_Joint Snap_Ring Mount_Resting_Joint Internal_Resting_Housing Resting_Housing Intake_Rocker_Arm	FlexValve_Rocker_Arm Output_Rocker_Arm Spring_Control Seat_Control_Spring Intake_Roller_Axle_Moving Cam_Roller_Moving Intake_Roller_Axle_Fixed Cam_Roller_Fixed Pivot_Axle FlexValve_Rocker_Center_Sleeve Output_Rocker_Center_Sleeve Grub Screw Intake_Resting_Joint_Foot Intake_Resting_Joint_Shaft Intake_Nut_Resting_Joint Retaining Plate - Roller Countersunk Torx Screw
Oil Control Module	Brake Oil Control Valve Mounting_Oil_Control	Brake Oil Control Valve OCV Mounting CDA Oil Control Valve	Brake Oil Control Valve Mounting_Oil_Control
Rocker Shaft	Rocker_Arm_Rod	Rocker_Arm_Rod	Rocker_Arm_Rod
Cam Shaft Module	Cam_Shaft Cam gear Camshaft Sensing	Cam_Shaft Cam gear Camshaft Sensing	Cam Lobe, Fixed, Intake Cam Lobe, Movable, Intake Cam Lobe, Fixed, Exhaust Cam Lobe, Fixed, Exhaust Brake Core Plug, DIN 443 - 26.5 - B - St Camshaft Tube, Machined Driveshaft Driver Pin Bearing Element Front Bearing Element Cam Gear FlexValve Actuator
Other Valvetrain Modules	Intake Valve Exhaust Valve Valve cover Valve spring Retainers, Cotters, Seats Harness	Intake Valve Exhaust Valve Valve cover Valve spring Retainers, Cotters, Seats Harness	Intake Valve Exhaust Valve Valve cover Valve spring Retainers, Cotters, Seats Harness
Assembly	Assembly of all Components	Assembly of all Components	Assembly of all Components

Table 6-2 provides attribute and cost comparison for each of the modules in valvetrain system for the three technologies evaluated. Comments provided below the cost numbers explain the reason for cost difference from a design and manufacturing perspective.

Table 6-2: Valvetrain Attribute & Cost comparison (15L Engine) (feed-through camshaft)

Valvetrain Attribute and Cost Comparison (Baseline vs CDA vs LIVC)								
ID	Module		Baseline	CDA	Delta	Baseline	LIVC	Delta
1	Exhaust Bridge Module	Quantity	6	6		6	6	
		Total Mass	0.88	1.58	-0.70	0.88	1.05	-0.17
		Total Cost	$14.94	$25.76	($10.83)	$14.94	$15.42	($0.49)
		Comments	CDA design includes a post that mounts on Cylinder Head to guide the exhaust bridge			Change in Rocker shaft position requires slight change in design of Exhaust bridge compared to baseline		
2	Intake Bridge Module	Quantity	6	6		6	6	
		Total Mass	0.87	0.72	0.15	0.87	0.87	0.00
		Total Cost	$8.66	$8.36	$0.30	$8.66	$8.66	$0.00
		Comments	Baseline Intake bridge is slightly heavier than CDA design			Same as baseline		
3	Exhaust Rocker Arm Module	Quantity	6	6		6	6	
		Total Mass	4.27	6.87	-2.60	4.27	5.19	-0.92
		Total Cost	$68.77	$120.14	($51.37)	$68.77	$71.69	($2.92)
		Comments	CDA module includes actuation mechanism to allow for cylinder deactivation. Oil pressure locks the Dowel pins thereby retracting the foot and not allowing exhaust valve to open resulting in cylinder deactivation			Change in Rocker shaft position requires slight change in design of Exhaust rocker compared to baseline		
4	Brake Rocker Arm Module	Quantity	6	6		6	6	
		Total Mass	7.71	5.42	2.30	7.71	7.71	0.00
		Total Cost	$91.41	$80.43	$10.99	$91.41	$91.41	$0.00
		Comments	CDA module uses a key gear to modulate exhaust valve to achieve exhaust braking, whereas Baseline technology uses a piston and spring assembly. The change in design is warranted due to			Same as baseline		

			packaging issue in cylinder head with baseline design					
5	Intake Rocker Arm Module	Quantity	6	6		6	6	
		Total Mass	5.89	7.89	-2.00	5.89	12.73	-6.84
		Total Cost	$71.33	$128.51	($57.18)	$71.33	$160.88	($89.56)
		Comments	CDA module includes actuation mechanism to allow for cylinder deactivation. Oil pressure locks the Dowel pins thereby retracting the foot and not allowing exhaust valve to open resulting in cylinder deactivation			FlexValve rocker consists of two rocker arms to achieve Late Intake Valve Closing. A moving cam lobe on camshaft is used to vary the intake valve lift. Also includes cylinder head machining required to provide clearance to FlexValve Rockers		
6	Oil Control Module	Quantity	2	4		2	2	
		Total Mass	1.06	7.89	-6.83	1.06	1.06	0.00
		Total Cost	$20.77	$112.87	($92.10)	$20.77	$20.77	$0.00
		Comments	CDA Module has 4 Mounting Blocks compared to just 2 in baseline. In addition to 2 brake OCVs, CDA module has 4 CDA OCVs. CDA mounting block can station 2 OCV valves whereas baseline can only station 1 OCV			Same as baseline		
7	Rocker Shaft	Quantity	2	2		2	2	
		Total Mass	6.04	6.04	0.00	6.04	6.04	0.00
		Total Cost	$64.96	$70.18	($5.22)	$64.96	$68.52	($3.56)
		Comments	More machining in CDA rocker arm (extra OCVs)			Same as baseline but cylinder head requires machining to facilitate change in rocker shaft position		
8	Cam Shaft	Quantity	1	1		1	1	
		Total Mass	21.10	21.10	0.00	21.10	26.29	-5.19
		Total Cost	$144.86	$144.86	$0.00	$144.86	$319.30	($174.44)
		Comments	CDA cam lobe profile will be different from baseline, but the final machining time would be same as baseline			LIVC has an assembled camshaft design compared to baseline (machined). It includes Fixed lobes, moving lobes, Driveshaft, Pin, bearing elements and FlexValve actuator to facilitate Late Intake Valve Closing mechanism		
9	Intake Valve		$34.91	$34.91	$ -	$34.91	$34.91	$ -

	Exhaust Valve		$39.81	$39.81	$ -	$39.81	$39.81	$ -
	Valve cover		$54.48	$54.48	$ -	$54.48	$54.48	$ -
	Valve spring		$38.74	$38.74	$ -	$38.74	$38.74	$ -
	Retainers, Cotters, Seats		$15.06	$15.06	$ -	$15.06	$15.06	$ -
	Harness	Quantity	1	1		1	1	
		Total Mass	0.20	0.45	-0.25	0.20	0.20	0.00
		Total Cost	$1.57	$6.96	($5.39)	$1.57	$1.57	$0.00
		Comments	CDA's additional OCV modules and Rockers require harness to control cylinder deactivation			LIVC valvetrain requires same harness for OCV as that of Baseline valvetrain		
10	Assembly of all Components	Quantity	NA	NA		NA	NA	
		Total Mass	NA	NA		NA	NA	
		Total Cost	$21.36	$25.13	($3.77)	$21.36	$23.51	($2.15)
		Comments	More T1 level Components than baseline - mainly in Oil Control Module			Same number of components to be assembled as baseline but more connection points		

7. SUMMARY AND CONCLUSION

The cost analysis conducted in this study relies on detailed and transparent cost models adhering to a set of detailed project boundary conditions (e.g., average 30k units/year, mature market conditions, manufacturing in the US, 2019/2020 manufacturing costs/rates, etc.,). The purpose of the cost analysis was not to evaluate what these new valvetrain technologies would cost at production inception, but rather to understand how competitive these component technologies could be in the long-term compared to their existing baseline counterparts, evaluated under the same boundary conditions (i.e., mature, high production volumes). If changes to the initial boundary conditions are made (i.e., production volumes lowered, market maturity assumptions modified, etc.), cost model updates would be required to address the differences. Alternatively, learning factors could be applied to account for key cost drivers such as production volumes, technology maturity, and market maturity. In this analysis no attempt is made to understand what the cost of the ICE technologies would be under alternative sets of boundary conditions.

In summary, the costs developed in this analysis should provide a good baseline of what the cost for these types of advanced ICE technologies could be based on within the defined boundary conditions. Because the actual industry is segregated in terms of adaptation levels, global volumes, maturity, etc., for these types of technologies, it is acknowledged that differences to the calculated analysis costs, versus actual implementation costs, between OEM to OEM, may fall somewhere in the range of +/-10% (this is different from learning factors discussed in Section **1.C**). There are a host of reasons why this may be true including: global manufacturing presence, global market presence, competitive landscape, existing long-term facility and labor contracts, working capital availability, cost of money, existing business partnerships (material suppliers, component suppliers, equipment suppliers, OEMs), existing company policies and culture, consumer market intelligence, company polices on profitability and risk taking, regulatory requirement conformance, and existing technology roadmaps all have an impact on what products and technologies in which suppliers and OEMs will continue to invest. This analysis does not assess the impact of these differences from OEM to OEM, though acknowledges they do exist, driving some differences to the calculated costs.

By integrating Oil Control Valves required for Cylinder deactivation operation onto the Compression brake mounting modules, the CDA installed valvetrain not only has the cost advantage but also provides various functional benefits. The system is able to change the valve lift between standard drive mode and engine brake mode in one engine cycle[7]. Eaton's CDA can control individual cylinders that allows it to activate only partial braking power if necessary. Deactivation of valve motions and fuel injection in two (of six) cylinders enables engine outlet temperatures of up to 520°C as a result of reduced air-to-fuel ratio[8].

At low loads Mechadyne's LIVC system can be used to increase the exhaust temperature (about 60ºC[5]) for thermal management of the after-treatment system. Elsewhere in the operating range it can be used for Miller cycling to yield economy benefits and at high loads to improve the volumetric efficiency for increased performance. The FlexValve lift curve family has been designed for late Miller cycle, with a phasing range of -10° to +40° (cam). **Figure 7-1** shows benefits of FlexValve system at different load characteristics.

For the FlexValve system, the full operating benefits from high load Miller and increased volumetric efficiency at higher engine loads and speeds would be achieved by using a turbocharger with an enhanced mass flow / boost pressure capability. The thermal management benefits at low loads via reduced volumetric efficiency, as well as the fuel economy benefits at medium loads can both be realized without any changes to the standard boosting system.

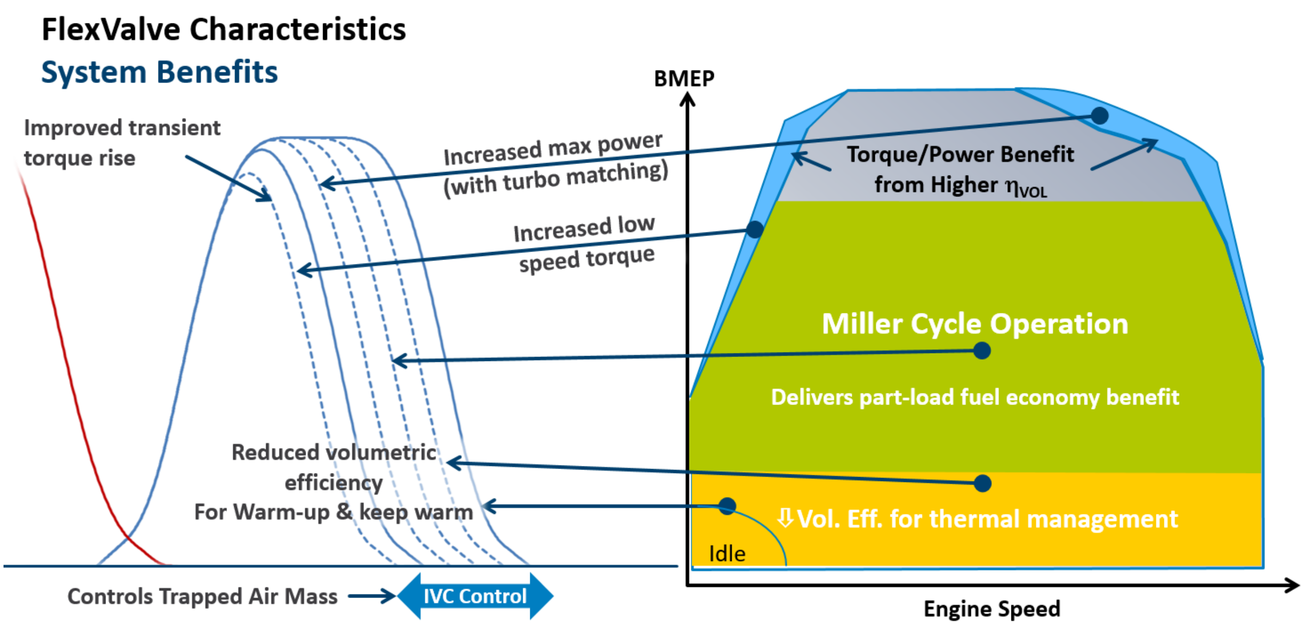


Figure 7-1: FlexValve LIVC Characteristics & System Benefits

Dynamic CDA has been demonstrated to a larger operating range of 1800rpm and up to 5.5bar BMEP[9]. LIVC can be used for thermal management up to 6 bar, however the system provides benefits across the full operating map as shown in **Figure 7-1**. This increased BMEP reduces emissions by improving aftertreatment thermal management while providing the welcome side effect of better fuel economy. These technologies can be used to reduce fuel consumption during active regen and to enable chemical de-SOx for LO-SCR systems at light and part load conditions.

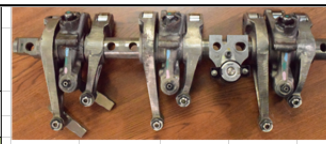
APPENDICES

8.A. Appendix A: Teardown Bill of Material, Additional Info

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Unit Mass	Length (mm)	Width (mm)	Height (mm)
Valvetrain				kg			
01	Exhaust Bridge Module		6	0.15			
1	Pin_Exhaust_Bridge	8620 Steel, Machining	6	0.03	26.97	17.27	0.00
2	Exhaust_Bridge	8620 Steel, Forging	6	0.12	77.96	17.54	22.26
02	Intake Bridge Module		6	0.14			
4	Intake_Bridge	8620 Steel, Forging	6	0.14	78.00	17.59	22.52
03	Exhaust Rocker Arm Module		6	0.71			
5	Nut_Resting_Joint	Steel, Cold forge	6	0.01	6.08	21.31	0.00
6	Resting_Joint	E52100 Steel, Machining	6	0.04	47.10	15.88	0.00
7	Shaft_Cam_Roller	P5 Steel, Machining	6	0.05	29.36	19.08	0.00
8	Cam_Roller	E52100 Steel, Machining	6	0.08	16.98	33.99	0.00
9	Exhaust_Center_Sleeve	4140 Steel, Stamping	6	0.02	27.48	36.57	0.00
10	Exhaust_Rocker_Arm	4140 Steel, Sand-Casting	6	0.52	160.00	160.00	45.00
04	Brake Rocker Arm Module		6	1.29			
11	Brake_Nut_Resting_Nut	Steel, Cold forge	6	0.00	6.62	14.56	0.00
12	Brake_Resting_Assembly	E52100 Steel, Machining	6	0.06	42.76	20.61	0.00
13	Snap_ring_Oil_Flow	Alloy Steel, Stamping	6	0.00	25.97	24.99	1.09
14	Cap_Oil_Flow	Alloy Steel, Stamping	6	0.01	13.27	23.36	0.00
15	Spring_Oil_Flow	Steel, Coiling	6	0.00	50.00	11.71	0.00
16	Oil_Flow_Assembly	E52100 Steel, Machining & Assembly	6	0.02	34.49	14.25	0.00
17	Brake_Shaft_Cam_Roller	Bronze, Machining	6	0.07	32.00	19.11	0.00
18	Brake_Cam_Roller	E52100 Steel, Machining	6	0.08	15.99	37.98	0.00
19	Brake_Center_Sleeve	4140 Steel, Stamping	6	0.03	37.90	36.58	0.00
20	Brake_Rocker_Arm	Gray Iron, Sand-Casting	6	1.01	155.00	110.00	40.00

Figure 8-1: Cummins X15 Valvetrain Teardown Bill of Material (1 of 2)

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Unit Mass	Length (mm)	Width (mm)	Height (mm)
Valvetrain				kg			
05	Intake Rocker Arm Module		6	0.98			
21	Intake_Nut_Resting_Joint	Steel, Cold forge	6	0.01	6.05	21.36	0.00
22	Intake_Resting_Joint	E52100 Steel, Machining	6	0.04	47.00	15.87	0.00
23	Intake_Shaft_Cam_Roller	P5 Steel, Machining	6	0.05	29.38	19.05	0.00
24	Intake_Roller_Arm	E52100 Steel, Machining	6	0.08	16.98	34.00	0.00
25	Intake_Center_Sleeve	4140 Steel, Stamping	6	0.02	27.43	36.82	0.00
26	Intake_Rocker_Arm	Gray Iron, Sand-Casting	6	0.79	190.00	100.00	30.00
06	Oil Control Module		2	0.53			
27	Bolt_Oil_Control	Steel, Cold forge	2	0.00	16.00	10.00	0.00
28	Oring_Oil_Control	Rubber, Injection Molding	2	0.00	1.75	20.00	0.00
29	Small_Oring_Oil_Control	Rubber, Injection Molding	2	0.00	1.75	15.00	0.00
30	Filter_Oil_Control	Overmolded filter	2	0.00	3.94	14.18	0.00
31	Oil_Control_Cover	Plastic, Injection Molding	2	0.00	58.39	33.80	23.20
32	Cap_Oil_Control	Alloy Steel, Stamping	2	0.02	24.00	31.15	0.00
33	Oil_Control_Internals_Cover	Commodity	2	0.05	57.80	28.50	18.92
34	Dowel_Oil_Control	Stainless Steel, Machining	2	0.01	11.21	12.96	0.00
35	Pin_Holder_Plate	Powder Metal	2	0.02	30.45	28.78	11.46
36	Pin_oil_Control	Alloy Steel, Machining	2	0.00	16.81	2.34	0.00
37	Bracket_Oil_Filter	Alloy Steel, Blanking	2	0.01	41.93	28.30	4.95
38	Internal_Pin	Alloy Steel Steel, Machining	2	0.00	24.97	7.92	0.00
39	Sleeve_Internal_Pin	Alloy Steel, Machining	2	0.00	4.40	6.26	0.00
40	Housing_Internal_pin	Al, Die-cast	2	0.04	31.57	30.62	28.67
41	Mounting_Oil_Control	Powder Metal	2	0.36	75.32	60.10	35.86
07	Rocker Shaft		2	3.02			
42	Rocker_Arm_Rod	4140 Steel, Machining	2	3.02	505.00	34.94	0.00
08	Cam Shaft		1	17.00			
43	Cam_Shaft	Steel, Machining	1	17.00	1,085	65.00	0.00
09	Other Valvetrain Modules						
	Intake Valve	Should-cost analysis is not performed for these modules as the evaluated valvetrain technology doesn't require any changes to these modules. Hence, a rough cost estimate and breakdown is used.	12	0.61			
	Exhaust Valve		12	0.05			
	Valve cover		1	0.62			
	Valve spring		24	0.04			
	Retainers, Cotters, Seats		24	0.04			
	Cam Phaser and Sprockets		1	0.57			
	Camshaft Sensing		1	3.48			
	Misc.		1	0.08			
10	Assembly						
A	Assembly of all Components	Assembly	1	0.00			



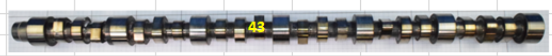
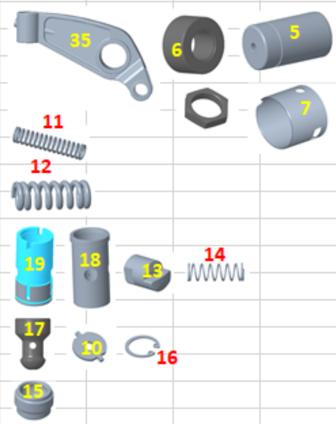


Figure 8-2: Cummins X15 Valvetrain Teardown Bill of Material (2 of 2)

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Unit Mass	Length (mm)	Width (mm)	Height (mm)
Valvetrain				kg			
01	Exhaust Bridge Module		6	0.263			
1	Pin_Exhaust_Bridge	8620 Steel, Machining	6	0.027	26.97	17.27	0.00
2	Exhaust_Bridge	8620 Steel, Forging	6	0.172	77.96	17.54	41.00
3	Post	E52100 Steel, Machining	6	0.064	105.00	10.00	10.00
3	Clip	Alloy Steel, Stamping	6	0.000			
02	Intake Bridge Module		6	0.120			
4	Intake_Bridge	8620 Steel, Forging	6	0.120	78.00	17.59	22.52
03	Exhaust Rocker Arm Module		6	1.145			
5	Shaft_Cam_Roller	P5 Steel, Machining	6	0.047	29.40	19.04	0.00
6	Cam_Roller	E52100 Steel, Machining	6	0.080	17.00	34.00	0.00
7	Center_Sleeve	4140 Steel, Stamping	6	0.018	27.48	36.57	0.00
8	Nut_Resting_Assembly	Steel, Cold forge	6	0.020	8.13	32.00	0.00
9	Snap_Ring_Internal	Alloy Steel, Stamping	6	0.001	22.29	21.67	0.97
10	Plate_Spring_Cover	16MnCr5, Stamping	6	0.005	23.41	20.71	1.95
11	Small_Spring	Steel, Coiling	6	0.005	43.25	11.86	0.00
12	Large_Spring	Steel, Coiling	6	0.009	48.06	16.00	0.00
13	Locking_Dowels	A2 Steel, Machining	12	0.002	9.23	6.94	0.00
14	Spring_Dowels	Steel, Coiling	6	0.000	19.14	3.95	0.00
15	Resting_Joint	E52100 Steel, Machining	6	0.009	11.37	15.87	0.00
16	Snap_Ring	Steel, Stamping	6	0.001	17.68	16.16	1.61
17	Mount_Resting_Joint	Powder Metal	6	0.018	23.55	16.09	0.00
18	Internal_Resting_Housing	16Mn5Cr, Machining	6	0.036	37.41	20.60	0.00
19	Resting_Housing	8620 Steel, Machining	6	0.061	50.40	25.94	0.00
20	Exhaust_Rocker_Arm	4140 Steel, Forging	6	0.832	210.00	120.00	40.00
04	Brake Rocker Arm Module		6	0.903			
5	Shaft_Cam_Roller	P5 Steel, Machining	6	0.047	29.40	19.04	0.00
7	Center_Sleeve	4140 Steel, Stamping	6	0.018	27.48	36.57	0.00
21	Brake_Cam_Roller	E52100 Steel, Machining	6	0.098	17.94	35.00	0.00
22	Bolt_Sleeve	Alloy Steel, Machining	6	0.009	15.50	17.91	0.00
23	Resting_Bolt	Steel, Cold Forge	6	0.016	49.38	11.18	0.00
24	Key_Gear	Powder Metal	6	0.017	22.76	23.28	19.71
25	Internal_Spring	Steel, Coiling	6	0.003	26.80	14.74	0.00
26	Internal_Gear_Sleeve	Powder Metal	6	0.015	20.30	20.27	0.00
27	Snap_Ring_Side	Alloy Steel, Stamping	6	0.000	9.43	8.55	0.80
28	Washer_Spring	Alloy Steel, Stamping	6	0.000	8.80	0.51	0.00
29	Spring_Alignment_Rod	Steel, Coiling	6	0.003	23.30	8.33	0.00
30	Alignment_Rod	E52100 Steel, Machining	6	0.005	18.80	8.94	0.00
31	Cap_Side	Alloy Steel, Stamping	6	0.001	3.06	10.11	0.00
32	Misc_Bolt	Steel, Cold forge	6	0.000	3.63	2.93	0.00
33	Misc_Snap_Ring	Alloy Steel, Stamping	6	0.000	18.47	16.37	0.88
34	Brake_Rocker_Arm	4140 Steel, Forging	6	0.669	155.00	65.00	40.00

Figure 8-3: 15L Engine Valvetrain w/ CDA Teardown Bill of Material (1 of 2)

Subsystem	Sub-subsystem / Module	Material & Primary Fabrication Process	QTY	Unit Mass	Length (mm)	Width (mm)	Height (mm)
Valvetrain				kg			
05	Intake Rocker Arm Module		6	1.315			
5	Shaft_Cam_Roller	P5 Steel, Machining	6	0.047	29.40	19.04	0.00
6	Cam_Roller	E52100 Steel, Machining	6	0.080	17.00	34.00	0.00
7	Center_Sleeve	4140 Steel, Stamping	6	0.018	27.48	36.57	0.00
8	Nut_Resting_Assembly	Steel, Cold forge	6	0.020	8.13	32.00	0.00
9	Snap_Ring_Internal	Alloy Steel, Stamping	6	0.001	22.29	21.67	0.97
10	Plate_Spring_Cover	16MnCr5, Stamping	6	0.005	23.41	20.71	1.95
11	Small_Spring	Steel, Coiling	6	0.005	43.25	11.86	0.00
12	Large_Spring	Steel, Coiling	6	0.009	48.06	16.00	0.00
13	Locking_Dowels	A2 Steel, Machining	12	0.002	9.23	6.94	0.00
14	Spring_Dowels	Steel, Coiling	6	0.000	19.14	3.95	0.00
15	Resting_Joint	E52100 Steel, Machining	6	0.009	11.37	15.87	0.00
16	Snap_Ring	Steel, Stamping	6	0.001	17.68	16.16	1.61
17	Mount_Resting_Joint	Powder Metal	6	0.018	23.55	16.09	0.00
18	Internal_Resting_Housing	16Mn5Cr, Machining	6	0.036	37.41	20.60	0.00
19	Resting_Housing	8620 Steel, Machining	6	0.061	50.40	25.94	0.00
35	Intake_Rocker_Arm	4140 Steel, Forging	6	1.002	210.00	120.00	40.00
06	Oil Control Module						
36	Brake Oil Control Valve	-----	2	0.173			
37	OCV Mounting	1040 Steel, Sand-casting	4	0.978	67.00	74.00	65.00
37	CDA Oil Control Valve	-----	6	0.173			
07	Rocker Shaft		2	3.022			
38	Rocker_Arm_Rod	4140 Steel, Machining	2	3.022	505.00	34.94	0.00
08	Cam Shaft		1	17.000			
39	Cam_Shaft	Steel, Machining	1	17.000	1,085	65.00	0.00
09	Other Valvetrain Modules						
	Intake Valve	Should-cost analysis is not performed for these modules as the evaluated valvetrain technology doesn't require any changes to these modules. Hence, a rough cost estimate and breakdown is used.	12	0.611			
	Exhaust Valve		12	0.051			
	Valve cover		1	0.615			
	Valve spring		24	0.042			
	Retainers, Cotters, Seats		24	0.041			
	Cam Phaser and Sprockets		1	0.570			
	Camshaft Sensing		1	3.480			
	Misc.		1	0.080			
10	Assembly						
A	Assembly of all Components	Assembly	1	0.000			



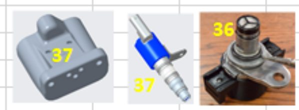


Figure 8-4: 15L Engine Valvetrain w/ CDA Teardown Bill of Material (2 of 2)

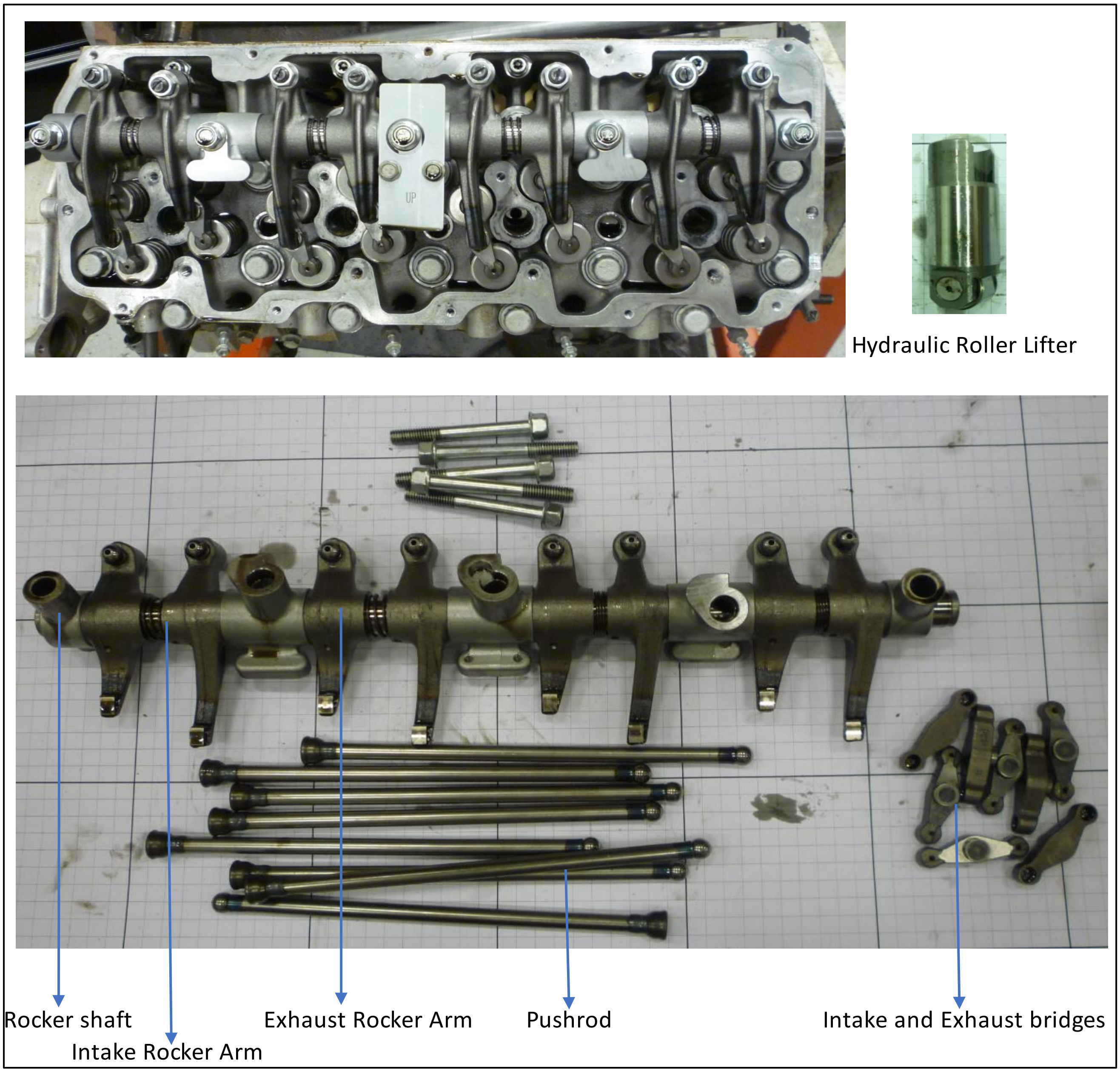


Figure 8-5: Type V Valvetrain – Components that are different from type III valvetrain)

BASELINE	CDA
Exhaust Rocker Arm Module	Exhaust Rocker Arm Module
Exhaust Rocker Arm	Exhaust Rocker Arm
Pushrod	Pushrod
Housing	Outer body
Swivel Rod	Inner body
Bearing-1	Latch pin
Bearing-2	Latch spring
Bolt	Socket
	Axle
	Axle clip
	Roller bearing
	Motion spring
	Retainer
	Clip
	Washer
	Shim
	Bolt

Figure 8-6: Type V Valvetrain – Exhaust Rocker Arm – Baseline vs CDA comparison)

Detailed Calculation				Section 1: Process Flow & Process Parameter Model Data Input					
Process Cost	Component Name	Material & Manufacturing Process	Finish Part Mass (kg)	Operation	Process & Machine Description	# Machine	# Parts per Machine	Cycle time (sec)	# Operators
$0.73	Pin_Exhaust _Bridge	8620 Steel, Machining	0.027	Billet	-----	1	1	1.00	0
$2.41			-----	Machining	Includes Turning, Drilling, Milling, Tool change and Handling cycle times	4	1	28.00	0.25
$1.04			-----	Heat treatment	Billet has a HRC range 52-60. Finished component has 75HRC	1	8004	62208	0
$1.42			-----	Grinding	Includes Cylindrical grinding, Horizontal surface grinding and Tool change	1	1	7.00	1
$0.03			-----	Wash	Rotary, Batch & Individual Washing with specialized spray nozzles	1	100	50.00	0

Figure 8-7: Cost Methodology Sample – Process flow steps & Manufacturing assumptions

Section 2: Select Applicable Rates and Assumptions Template (RaAT) Values					
Material ID	Material rate per kg	Labor ID	Labor rate per hr	MOH ID	MOH rate per hr
Ni-Cr-Mo Steel-8620, Bar	1.46	Not Applicable	0.00	Not Applicable	0.00
Not Applicable	0.00	Lathe/Turning Operator-336300	36.49	CNC Machining, LC	30.38
Not Applicable	0.00	Not Applicable	0.00	Heat Treat, SMS, LMC	50.00
Not Applicable	0.00	Lathe/Turning Operator-336300	36.49	Grinding, SS	45.00
Not Applicable	0.00	Not Applicable	0.00	Washing Equipment, LC	22.50

Figure 8-8: Cost Methodology Sample – Rates database preview

8.B. Appendix B: Glossary

Following are some terms and acronyms that will typically be associated with this study and found within the documentation.

Assembly	A group of interdependent components joined together to perform a defined function (e.g., turbocharger assembly, high pressure fuel pump assembly, high pressure fuel injector assembly).
CBOM (Comparison Bill of Materials)	A system bill of materials, identifying all the subsystems, assemblies, and components associated with the technology configurations under evaluation. The CBOM records all the high-level details of the technology configurations under study, identifies those items which have cost implication as a result of the new versus base technology differences, documents the study assumptions, and is the primary document for capturing input from the cross-functional team.
Cost Estimating Models	Cost estimating tools are used to calculate operation and process parameters for primary manufacturing processes (e.g., injection molding, die casting, metal stamping, forging). Key information

	calculated from the costing estimating tools (e.g., cycle times, raw material usage, and equipment size) are entered into process flow template and cost model worksheets referred to as MAQS worksheets
COSTING Databases	The five (5) core databases that contain all the cost rates for the analysis. (1) The material database lists all the materials used throughout the analysis along with the estimated price/pound (or kg) for each. (2) The labor database captures various automotive, direct labors, manufacturing jobs (supplier and OEM); along with the associated mean hourly labor rates. (3) The manufacturing overhead rate database contains the cost/hour for the various pieces of manufacturing equipment assumed in the analysis. (4) A mark-up database assigns a percentage of mark-up for each of the four (4) main mark-up categories (i.e., end-item scrap, SG&A, profit, and ED&T), based on the industry, supplier size, and complexity classification. (5) The packaging database contains packaging options and costs for each case.
CFT (Cross Functional Team)	A group of people with different functional expertise working toward a common goal.
CMAT (Cost Model Analysis)	The document used to display and roll up all the incremental associated costs as defined by the CBOMs.
Delta	An incremental change in a variable, the difference.
ED&T (Engineering, Design, And Testing)	An acronym used in accounting to refer to engineering, design, and testing expenses.
MAQS (Manufacturing Assumption and Quote Summary) Worksheet	Standardized template used in the analysis to calculate the mass production manufacturing cost, including supplier mark-up, for each system, subsystem, and assembly quoted in the analysis. Every component and assembly costed in the analysis will have a MAQS worksheet. The worksheet is based on a standard OEM

	(original equipment manufacturer) quote sheet modified for improved costing transparency and flexibility in sensitivity studies. The main feeder documents to the MAQS worksheets are process maps and the costing databases.
Process Maps / Process Flow Templates	Detailed process flow charts used to capture the operations and processes and associated key manufacturing variables involved in manufacturing products at any level (e.g., vehicle, system, subsystem, assembly, and component).
P-VCSM (Powertrain–Vehicle Class Summary Matrix) Process Maps	Records the technologies being evaluated, the applicable vehicle classes for each technology, and key parameters for vehicles or vehicle systems that have been selected to represent the new technology and baseline configurations in each vehicle class to be costed.
Quote	The analytical process of establishing a cost for a component or assembly.
SG&A (Selling General and Administrative)	An acronym used in accounting to refer to Selling, General and Administrative Expenses, which is a major non-production costs presented in an Income statement.
System	A group of interdependent subsystems, sub-subsystems, assemblies, and/or components working together to create a vehicle primary function (e.g., engine system, transmission system, brake system, fuel system, suspension system).
System CMAT (Cost Model Analysis Template)	The document used to display and roll up all the subsystem incremental costs associated with a system (e.g., engine, transmission, steering) as defined by the CBOMs.
Subsystem	A group of interdependent sub-subsystems, assemblies and/or components, required to create a functioning subsystem. For example, the engine system contains several subsystems including crank drive subsystem, cylinder block subsystem, cylinder head subsystem, fuel induction subsystem, and air induction subsystem. The entire engine assembly excluding – Tailpipe, Induction Air Dampeners with Tubes, Transmission, Power Steering Pump, A/C Compressor, Fuel Cooler,

	Radiator Fans, Coolant After Run Coolant Pump, Coolant Tube, Clutch, Clutch Case, Fan and Fan Drive, fixed to engine, Fan Case, Cooling Baffles, Engine Cover/Beauty Cover, Engine Mounts, Engine Oil, Vacuum Pump (electrical), Converter (not integrated to Exhaust Manifold).
Subsystem CMAT (Cost Model Analysis Templates)	The document used to display and roll up all the sub-subsystem, assembly, and component incremental costs associated with a subsystem (e.g., fuel induction, air induction, exhaust), as defined by the Comparison Bill of Material (CBOM).
Sub-subsystem	A group of interdependent assemblies and/or components required to create a functioning sub-subsystem. For example, the air induction subsystem contains several sub-subsystems including turbocharging, heat exchangers, pipes, hoses, and ducting.
Sub-subsystem CMAT (Cost Model Analysis Templates)	A group of interdependent assemblies and/or components required to create a functioning sub-subsystem. For example, the air induction subsystem contains several sub-subsystems including turbocharging, heat exchangers, pipes, hoses, and ducting.
ICE	Internal Combustion Engine
T-1	Tier-1 Supplier
T-2	Tier-2 Supplier

8.C. Appendix C: References / Endnotes

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