The DELTA Model: Improved Evaporative Emissions Modeling for EPA MOVES
DRAFT

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This report documents the assumptions, data sources, calculations and limitations used to estimate on-road vehicle evaporative emissions due to multi-day diurnal cycles using the DELTA (Diurnal Emissions Leaving To Atmosphere) model. This new model is associated with updates to the EPA MOVES model in conjunction with the proposed Tier 3 rulemaking.

I. Summary

The MOVES 2010a model contains evaporative emissions estimates based on older data that could not adequately model emissions beyond one day of diurnals. The DELTA model was created to update MOVES 2010a evaporative vapor emissions to extend beyond one day of diurnals as well as taking advantage of newer datasets. Curves generated by the DELTAmodel would replace the cumTTVcoeffs table found in the default MOVES database, as well as including changes to the MOVES Java code to account for new calculations steps included with the replacement curves. The DELTA model runs using Python 2.6.2 and associated open source libraries; however, it is designed to run internally to the MOVES model and should not require interaction from MOVES users.

The DELTA model uses the Wade-Reddy equation for vapor generated from the vehicle fuel tank and backpurge factors derived from a previous EPA marine canister study. By modeling a single vehicle's response over the course of multiple diurnals, the DELTA model can generate a relationship between tank vapor generated (TVG) and tank vapor vented to the atmosphere (TVV) as a TVG – TVV curve. Multiple single vehicle models can then be combined to create a single, weighted TVG – TVV curve representative of the entire fleet for use in the MOVES model, including specific vehicle standard groups such as Pre-enhanced, Enhanced/Tier 1 and Tier 2.

The results from the DELTA model were compared to multiple day diurnal emissions measured as part of the CRC E77 project. It was shown that the DELTA model under ideal conditions under-predicts diurnal emissions compared to the real world data seen from E77. Further exploration revealed that many of the vehicles in the E77 dataset captured significantly less vapor than their rated canister capacity before vapor breakthrough which the DELTA modeling was based upon. A supplementary approach was then developed to adjust the DELTA model results to account for this non-ideal behavior.

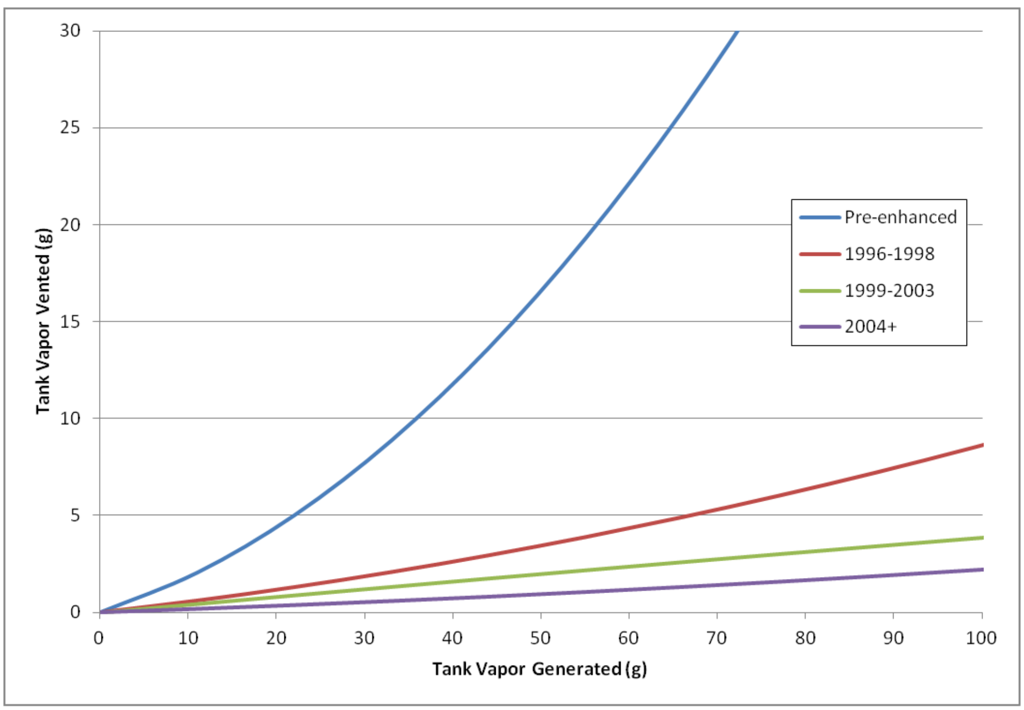
II. What is the DELTA model?

This section provides background information regarding the current evaporative inputs in the MOVES 2010a model and why it they would be updated, what the DELTA model would replace in MOVES, and how the DELTA model would function within the MOVES model.

a. Why create the DELTA model?

The MOVES 2010a evaporative emissions estimates were based on IUVP vapor venting emission data collected between 1994 and 1996 (please see EPA Development of Evaporative Emissions Calculations for the Motor Vehicle Emissions Simulator MOVES2010 – March 2010 for more information). This data provides SHED evaporative emissions (in grams) for a large set of vehicles undergoing a single diurnal cycle. This data was then fit with a quadratic equation as shown in Figure 1.

Figure 1 - MOVES 2010a Vapor Venting Curves



Note: These curves apply to a vehicle fleet average of 11 gallons of tank headspace

Although the IUVP data in MOVES 2010a provided a large and robust dataset for one day of emissions, it was not capable of modeling evaporative emissions beyond one day of diurnal cycling, as desired for future scenarios. Furthermore, using quadratic equations to fit diurnal emissions was not accurately representing the actual response of canister breakthrough; mainly a prediction of non-zero breakthrough at very low vapor generation not seen in actual data due to canister storage capacity. Therefore, the DELTA model was developed in order to more accurately represent multiple day canister loading and breakthrough.

b. What is DELTA replacing in MOVES?

The previous breakthrough emissions equations were contained in the cumTVVcoeffs table found in the MOVES database. DELTA would replace these equations with a new set of equations generated within the DELTA model. The DELTA model was focused primarily on light duty vehicles and therefore this section of the database received the most rigorous changes. However, both motorcycles and heavy duty vehicles also benefit from the new calculation of multiple day diurnals and allow for the addition of new data sources for diurnal information at a later date. The DELTA model also introduces changes to the MOVES Java code in order to take into account the nature of multiple day diurnal cycles. These new features (including the DELTA equations) can be deactivated if running MOVES using the older evaporative model is desired.

c. How does the DELTA model function?

The DELTA model is currently written in Python 2.6.2 and uses several extensions to the base Python library. Equation fitting was done using a custom Microsoft Excel spreadsheet, based on a least-squares approach fitting a rotated hyperbolic section. This process is explained in more detail in later sections. More information regarding the MOVES model can be found at the EPA MOVES website (http://www.epa.gov/otaq/models/moves/index.htm). It is important to note that the DELTA model was written to be run only internally to the MOVES model for the generation of TVG – TVV curves. Interaction between the DELTA model and MOVES users is not required or expected for evaporative emissions modeling or SIP analyses. A copy of a standalone version of the DELTA model source code can be found in Appendix A for review.

III. Modeling a single ideal vehicle

This section begins a walkthrough of the theory behind the DELTA model. Beginning with a single vehicle, this section provides information on how vapor is generated during a diurnal cycle, how vapor is captured by an evaporative system, how systems may gain capacity during the cooling part of a diurnal cycle, and how a diurnal can be extended to multiple days in the model.

a. Tank vapor generation - The Wade-Reddy model

The source of diurnal emissions we are concerned about in the DELTA model is evaporation of gasoline vapor from a vehicle's tank during a rise in temperature. The evaporation rate is dependent on how much temperature change has occurred, the volatility of the fuel (RVP), the ethanol content of the fuel (E0, E10, etc...) and the altitude of the vehicle over sea level. Generally as temperature change, fuel volatility, and altitude increase, vapor evaporation also increases. Ethanol effects vary in that vapor evaporation increases as ethanol concentration increases until approximately 15% ethanol content. At higher concentrations evaporation decreases with increasing ethanol due to nonlinear effects on fuel volatility, with volatility returning to E0 levels around 50% ethanol content and decreasing from there.

In 1989 Samuel Reddy published SAE paper 892089 which characterizes the evaporation rates for different temperature ranges, volatilities, altitudes and ethanol concentrations. From these results a model of gasoline evaporation rates was created, as seen in Equation 1:

Equation 1 – Wade-Reddy Tank Vapor Generation

$$\boldsymbol{tank\ vapor\ generated = Ae^{B*RVP}\left(e^{C*T_{high}} - e^{C*T_{low}}\right)}$$

Where A, B and C are coefficients based on altitude and ethanol content

The Wade-Reddy model for fuel evaporation is currently used in MOVES in order to calculate evaporative emissions for differing locations and fuel properties. DELTA continues to utilize the Wade-Reddy model for the RVP and temperature ranges needed for evaporative emissions modeling in MOVES. Further information regarding gasoline vapor generation is beyond the scope of this document; please refer to SAE 892089 for more details.

b. Tank vapor venting

Vehicle evaporative systems contain a bed of activated carbon in order to capture vapors generated from a vehicle fuel tank during diurnal heating. This activated carbon is usually contained in a canister present between a vehicle tank vent and the atmosphere. Vapor leaving a vehicle fuel tank without being captured by the carbon canister is usually referred to as breakthrough. The terms canister, activated carbon, or carbon bed used in the next sections refer to this canister of activated carbon. The amount of vapor leaving the fuel tank through this canister depends not only on the amount of fuel vapor generated, but also on properties of the carbon bed. These properties are briefly explained in the next subsections, an in-depth discussion of carbon properties is beyond the scope of this document.

i. Activated carbon properties - butane working capacity

Activated carbon is able to store evaporated fuel vapors through adsorption onto its surface. The rate and quantity of this adsorption is affected by properties of the carbon including: the extent of carbon bed heel, the number and size of pore sites, the geometry of the carbon canister, the presence of channeling in the carbon bed and the material the activated carbon was created from. These properties are usually aggregated into the total weight of fuel vapor a canister is capable of adsorbing (usually in grams), known as the butane working capacity (BWC). The EPA procedure for determining the BWC of a canister can be found in CFR 86.132-96; the ASTM procedure for determining BWC can be found in ASTM D-5228-92. While we are aware that carbon properties may affect canister performance in ways that cannot be captured using BWC, we have focused on BWC for the DELTA model at this time. Improvements incorporating these properties may be incorporated into a future version of the DELTA model.

ii. Canister loading and non-linear effects

Canister adsorption is also affected by the temperature of the canister as well as the rate of vapor loading onto the canister. Activated carbon adsorption rates are inversely proportional to the temperature of the carbon bed. As the temperature of the canister rises, the rate of adsorption decreases while the rate of desorption increases. This has the effect of lowering the

BWC with higher temperatures. This effect is magnified by the exothermic nature of vapor adsorption onto the carbon bed. High vapor loading rates (such as those found during onboard refueling vapor recovery, ORVR) significantly increase the temperature of the carbon bed, reducing the capacity of the vapor storage. Conversely, this effect can increase the effectiveness of a canister clean-out event if the canister is heated due to the increased desorption rates at high temperatures.

Canister loading does not occur linearly throughout the carbon bed. While it is convenient to think of vapor loading into the canister similarly to a glass filling with water (and eventually overflowing when the glass is full), fuel vapors form a concentration gradient throughout the carbon bed. During short term loading events (such as ORVR), the fuel vapor does not have sufficient time to spread into a gradient before a clean-out event takes place. However, a diurnal lasting several days provides ample time for some vapor to move beyond the front of high concentration near the inlet to the canister. This can cause a 'bleed' effect where fuel vapor is escaping the canister long before the canister has adsorbed to its rated capacity. Differing carbon properties alter the concentration gradient and can affect the rate of bleed to the atmosphere.

In the DELTA model canister loading occurs without temperature or bleed effects. Both of these effects require input beyond the capabilities of MOVES (canister loading rate, specific carbon quality) and would also significantly increase the time to run the DELTA model. Methods to incorporate these effects into the next version of the DELTA model are under development.

c. Canister backpurge

Durring the cooling phase of a diurnal, fresh air from the atmosphere is drawn back into a vehicle fuel tank and across the carbon bed in the canister. This fresh air causes some fuel vapor to desorb from the carbon and return to the fuel tank, a process called backpurge, or passive purge (as opposed to active purge, where vehicle intake vacuum is used to draw fresh air through the canister and into the engine to achieve the same effect). Backpurge essentially creates additional vapor capacity within the canister during the cooling phase of a diurnal. The amount of additional capacity created is dependent on the magnitude of the temperature change as well as the amount of vapor already contained in the canister. Backpurge was studied by EPA as a control strategy for marine vehicle evaporative systems lacking active purge (EPA420-R-08-014, Chapter 5). Since this phenomenon also occurs within vehicle canisters the rates derived from this study are appropriate for use with onroad vehicles as well, it also served as the basis for backpurge in the DELTA model.

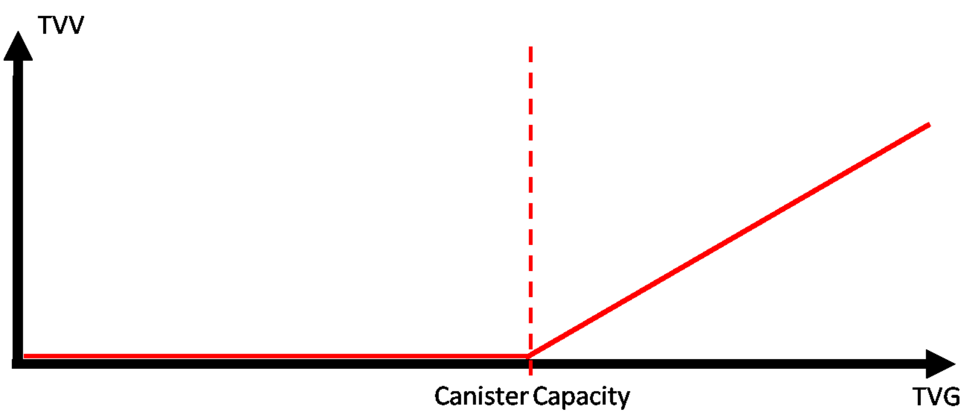
d. Multiple day diurnal emissions for a single ideal vehicle

Modeling a single vehicle requires combining the above three topics (tank vapor generation, canister loading, and canister backpurge) in a way that emulates real-world multiple day diurnal cycles. This includes calculating the amount of vapor generated during the warming phase of a diurnal, loading the canister and accounting for potential breakthrough, and calculating additional canister capacity gained through backpurge during the cooling phase of a diurnal. The following subsections walk through how the DELTA model would combine these topics to calculate multiple day diurnal emissions for a single vehicle.

i. Construction of a TVG - TVV curve

Although it is possible to track diurnal emissions through time, we have decided in the DELTA model to associate diurnal emissions with the total amount of vapor generated throughout multiple diurnal cycles. In this way, diurnal emissions (tank vapor vented, TVV) become a function of the amount of vapor generated in the tank (tank vapor generated, TVG) independent of how that vapor was generated. Therefore, the TVG - TVV equation is based entirely on canister properties specific to the vehicle being modeled (canister working capacity and backpurge characteristics). This allows for the flexibility of differing fuel properties or diurnal temperature profiles without having to recalculate entirely new emission equations.

Figure 2 - Ideal Vehicle TVG-TVV Curve

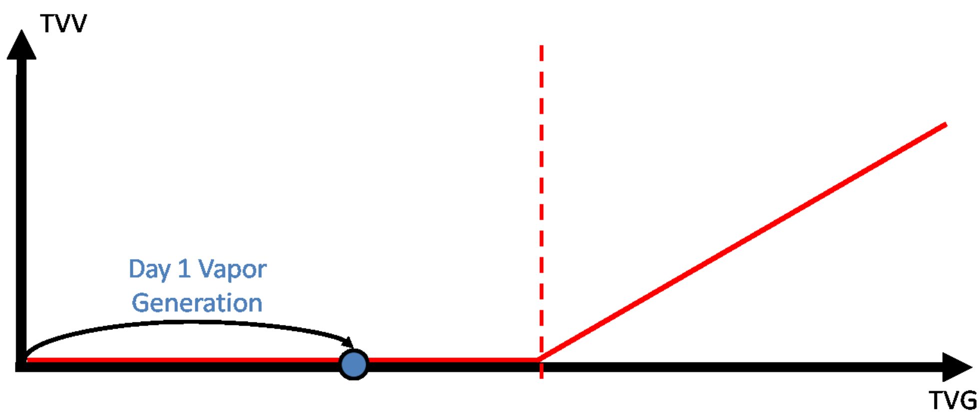


As shown in Figure 2, the model of an ideal vehicle TVG - TVV equation is simple. Starting with a clean canister, vapor being generated is entirely captured in the canister, resulting in no breakthough emissions. At a point where the amount of vapor generated has reached the working capacity of the canister, breakthough begins to occur. The amount of breakthrough after this point is equal to the amount of vapor generated beyond this point (due to the canister's inability to adsorb additional vapor beyond its capacity), appearing as a line with slope equal to one.

ii. Using a TVG - TVV curve for multiple diurnals

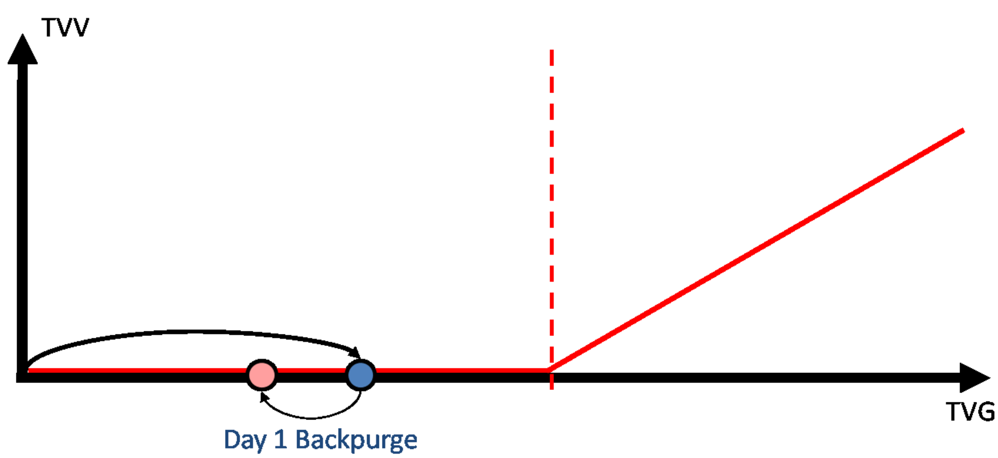
The DELTA model uses the TVG - TVV curve illustrated in the above subsection III.d.i to calculate breakthrough emissions occurring after several diurnal temperature cycles. This is accomplished by calculating the total tank vapor generated for a given diurnal, adding that to the previous total vapor generation and then using the curve for TVV at this TVG point. The total vapor generation is then adjusted in the negative direction to account for the additional capacity created by backpurge during the diurnal cooling phase. This process is illustrated in the next set of figures.

Figure 3 - TVG-TVV Day 1 Vapor Generation



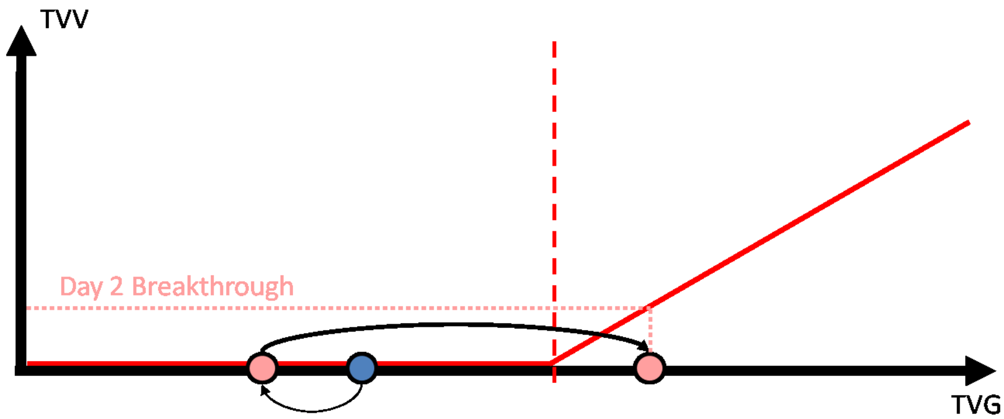
In Figure 3, the diurnal vapor generation for one day has been calculated and found on the TVG - TVV curve. In this example, the vapor is entirely captured by the canister resulting in zero breakthough for the first day. Therefore, DELTA would report a value of zero breakthough for this vehicle on day one in MOVES.

Figure 4 - TVG-TVV Day 1 Backpurge



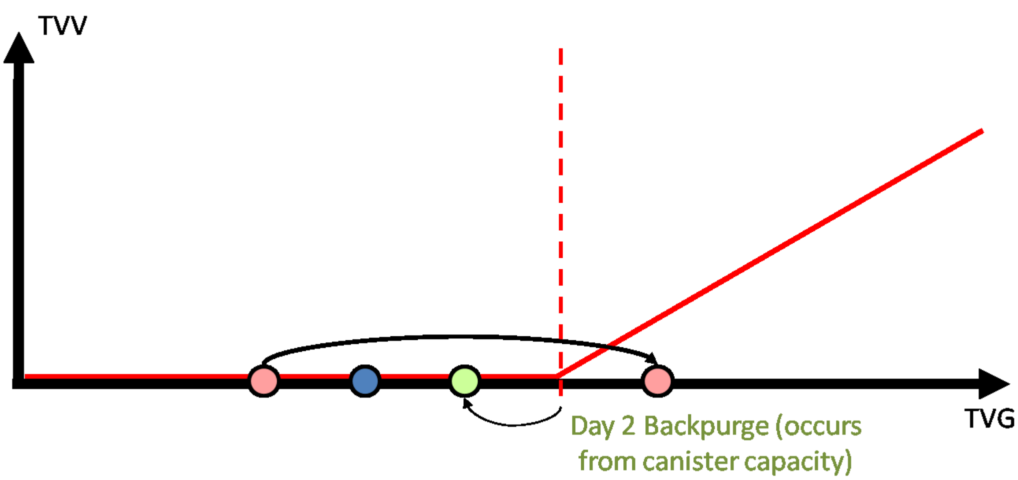
In Figure 4, the backpurge has now been calculated and subtracted from the total vapor generation (accounting for the additional capacity created by the backpurge during diurnal cooling). Calculations for a day two diurnal temperature cycle would begin at this point.

Figure 5 - TVG-TVV Day 2 Vapor Generation



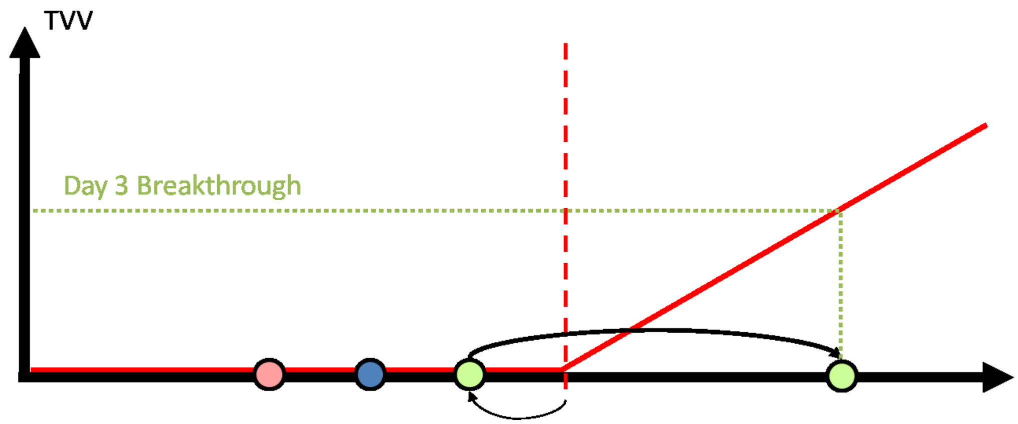
In Figure 5, the second day of diurnal vapor generation has been calculated and added to the previous total vapor generation from the previous day. In this example, the total vapor generation has now exceeded the working capacity of the canister and vapor has begun to breakthrough. The amount of breakthough is found on the TVG - TVV curve and reported by DELTA.

Figure 6 - TVG-TVV Day 2 Backpurge



In Figure 6, the backpurge has now been calculated and subtracted from the total vapor generation at the point of the canister capacity. Backpurge can only affect vapor that is actually stored in the canister, vapor that is lost due to breakthrough cannot be recovered back into the vehicle tank, and therefore cannot be counted either for backpurge or as part of the total vapor generation. The DELTA model accounts for the working capacity of the canister and calculates where backpurge should begin from accordingly. Calculations for a day three diurnal temperature cycle would begin at this point.

Figure 7 - TVG-TVV Day 3 Vapor Generation



In Figure 7, the third day of diurnal vapor generation has been calculated and added to the prvious total vapor generation from the previous days. Again, the amount of breakthrough is found using the TVG - TVV curve, and the backpurge is appropriately subtracted from the total vapor generation beginning at the working capacity of the canister. This process will continue for as many days as desired or necessary for MOVES operation.

Figure 8 - TVG-TVV Vapor Loading and Backpurge Summary

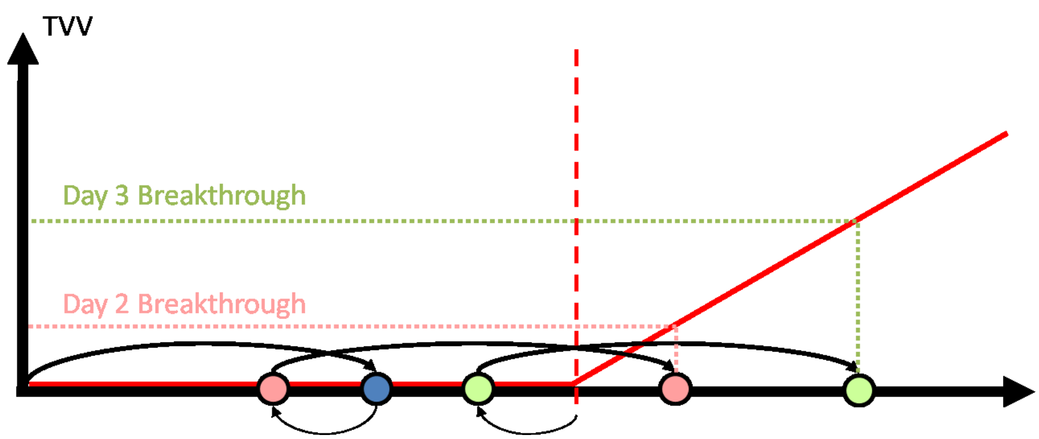


Figure 8 summarizes the calculations completed by DELTA to determine breakthrough vapor emissions for a single ideal vehicle. The ability to model a single vehicle is the first step to creating a model capable of estimating diurnal evaporative emissions for an entire fleet of vehicles. A discussion of how the single vehicle models created in the above section can be combined into a single fleet model follows in the next section.

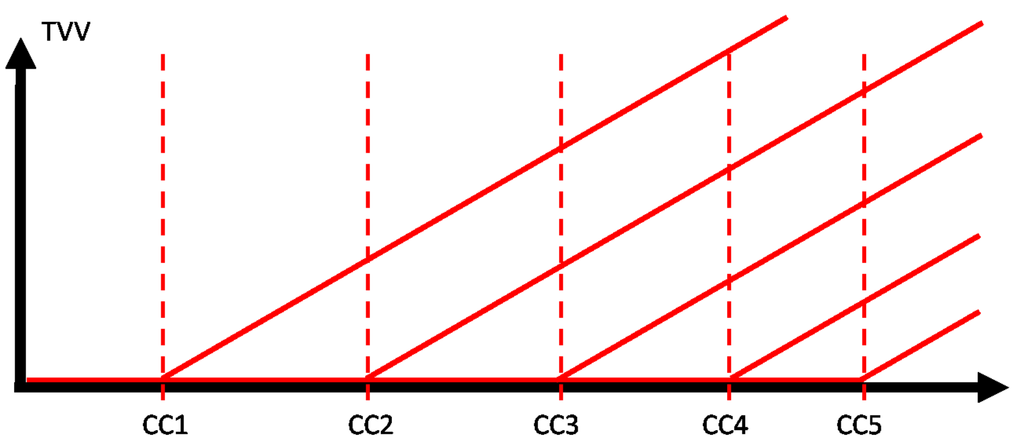
IV. Modeling an ideal fleet

This section continues the walkthrough of the DELTA model. Using the model of a single ideal vehicle explained in section III as a starting point, this section explains how DELTA can model breakthrough emissions of an entire fleet. This includes building a fleet average TVG - TVV curve, finding and using a fleet average canister size and tank volume, and producing a fleet average TVG - TVV curve for use in the MOVES model.

a. Multiple single vehicle models

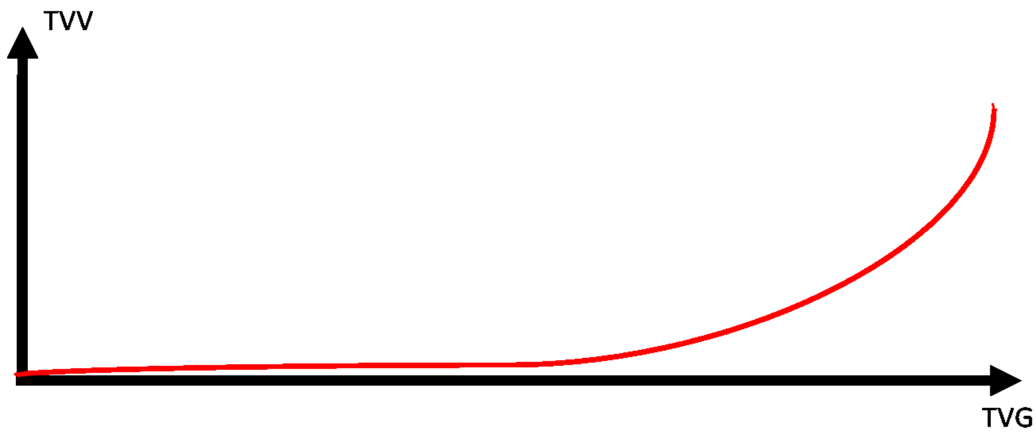
In order to model a representative fleet for a given vehicle type and model year, multiple versions of the single vehicle model (discussed in Section III) are constructed and weighted together. This weighted model is used as the fleet average TVG - TVV curve for calculating diurnal emissions in the MOVES model. Each single vehicle line depends on that vehicle's canister properties and backpurge characteristics. Properties needed for the calculation of vapor generation only (such as tank size) are not included in constructing the multiple vehicle models; these properties will be factored into the weighted model at a later point.

Figure 9 - Multiple Individual Vehicle TVG-TVV Models



Individual vehicle models are weighted together in DELTA using fractional percentages of the user's choice. For the MOVES model, we formed each average model year fleet from individual vehicles models of the top 30 selling vehicles of that model year. Data for canister properties were determined from EPA certification data for these vehicles. These models were then weighted together based on the volume of sales for each vehicle within a given model year. This produces a single TVG - TVV curve representing a weighted average of all individual vehicle models within that vehicle type and model year.

Figure 10 - Combined/Weighted Fleet Average TVG-TVV Model

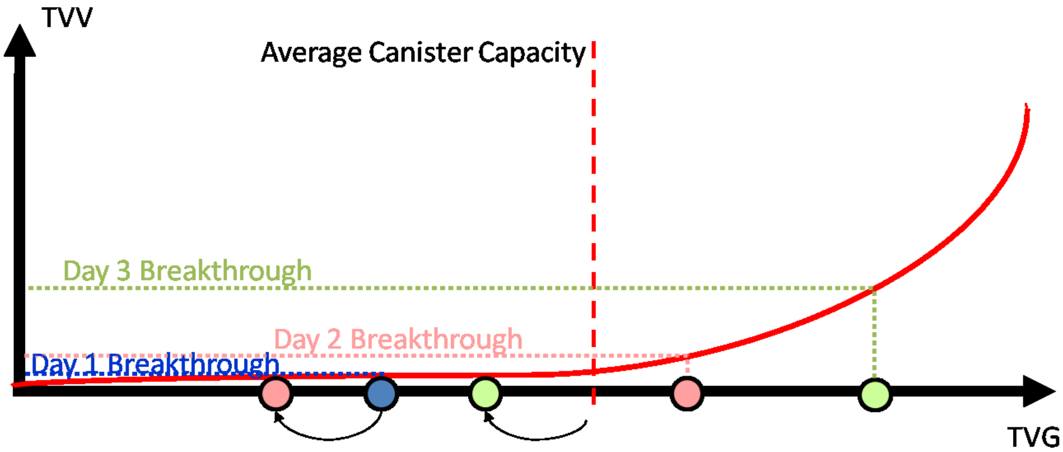


This curve no longer has the characteristic rise at a specific canister capacity. This is due to some vehicles beginning to break through while others remain at zero breakthrough; caused by differences in canister properties expressed in the individual vehicle models. The method for handling the average canister breakthrough point on the weighted TVG - TVV curve is discussed in the next subsection.

b. Fleet average canister size and tank volume

The same methodology for calculating single vehicle breakthrough emissions (as discussed in section III.d.ii) can be used with the fleet average TVG - TVV curve developed in the previous subsection. However, unlike the single vehicle models, there are multiple canister capacities and tank volumes that comprise the weighted curve for the fleet. Since tank size is used in the calculation of TVG and canister capacity is used in the calculation of backpurge and TVV (for determining when breakthrough will occur as well as what value of TVG backpurge will occur from), these values must also be aggregated from each of the single vehicle models. DELTA uses the same weighting factors applied to the single vehicle TVG – TVV curves to calculate a single weighted tank size and canister size based on the individual tank and canister sizes found in the fleet. These weighted average tank and canister sizes are then used in the fleet average model in a similar way to how they would be applied in the single vehicle models. A summary of this method can be found in the figure below.

Figure 11 - Fleet Average TVG-TVV Summary



We are aware that using a single average tank and canister capacity to represent an entire vehicle may be over-simplified in some circumstances. Cases such as a small number of passenger vehicles modeled in the same group as a large number of pickup trucks may produce larger breakthrough than expected due to a large average tank size producing high amounts of vapor while coupled with less storage due to a smaller average canister capacity. One vehicle breaking through significantly before other vehicles in the aggregate model may also cause higher than expected breakthrough due to a small but non-zero fleet average TVG – TVV line occurring well before the average canister capacity of the fleet is reached. Usually, tank volume and canister capacity are well correlated over an entire model year fleet and therefore the tank volume and canister capacity simplifications should largely not affect results. However, this is an area under consideration for improvement in the next version of the DELTA model.

c. Producing a fleet average curve equation for MOVES

The EPA MOVES model requires the average tank size, the average canister capacity, the backpurge percentage and a fleet average TVG – TVV curve from DELTA as inputs to its evaporative emissions module for on-road vehicle emissions modeling. Most of these can be converted directly to MOVES format as single numbers, however; the TVG – TVV curve must first be converted to a continuous equation before use in the MOVES model. A rotated hyperbola was identified as the most similar continuous equation to the fleet average TVG – TVV lines created by the DELTA model, and is of the form:

Equation 2 - Generic Form of Hyperbolic Section

$$y = \frac{-(Bx + E) \pm \sqrt{(Bx + E)^2 - 4C(Ax^2 + Dx + F)}}{2C}$$

A least-squares approach was used to determine the six variables needed to fit the TVG – TVV curve to this form of the hyperbolic equation. Special care should be taken to fit the values of the curve less than 200 grams TVG; an iterative least-squares algorithm has been shown to provide less than ideal fits for this region of the TVG – TVV curve.

The results of the DELTA model fitted TVG – TVV curve as well as other data points discussed earlier in this subsection for all model years 1974 and later can be found in the MOVES database table cumTVVcoeffs. In addition to DELTA modeling results and legacy evaporative coefficients, the cumTVVcoeffs table also contains vapor leak rates and leak prevalence; topics which are beyond the scope of this document.

V. Comparison of an ideal fleet to E77 diurnal data

This section compares the ideal models described in the previous section to real world diurnal data obtained through the CRC E77 project. As part of this project, several vehicles were tested in an evaporative SHED over three days with the resulting evaporative emissions reported on a continuous basis in ten minute intervals. In this section, the inputs used for the DELTA modeling of the E77 test vehicles are discussed, the results of the DELTA model are compared to those from the E77 multiple day evaporative shed results, and data supporting DELTA under-predicting vehicle breakthrough emissions are discussed. For more information regarding the CRC E77 project, including test procedures, specific vehicle information and more detailed results, please see E77-2c at (http://crcao.org/publications/emissions/index.html).

a. Constructing DELTA inputs from the E77 vehicle fleet

The total set of vehicles used in this comparison was comprised of 21 vehicles and 47 individual tests, divided into three subsets based on emission certification class. Of the 47 tests, 9 tests were considered pre-enhanced (vehicles pre-1996), 23 tests were considered Tier 1/enhanced (vehicles 1996-2003) and 15 tests were considered Tier 2 (vehicles 2004+). A tank volume headspace average of 10.5 gallons, a backpurge value of 35%, and equal weighting between vehicles was used for all three subsets. Vehicle canister capacities used in the DELTA model follow in the tables below: The vehicle canister capacities were derived from EPA vehicle certification data and evaporative family codes.

Table 1 - Pre-enhanced DELTA Model Input

Model / ID	Weighting Factor	Canister Size
6915	0.1111	41
6919	0.1111	90
6922	0.1111	90
6925	0.1111	47
6926	0.1111	57
6927	0.1111	50
6970	0.1111	68
6973	0.1111	68
6985	0.1111	75

Table 2 - Enhanced/Tier 1 DELTA Model Input

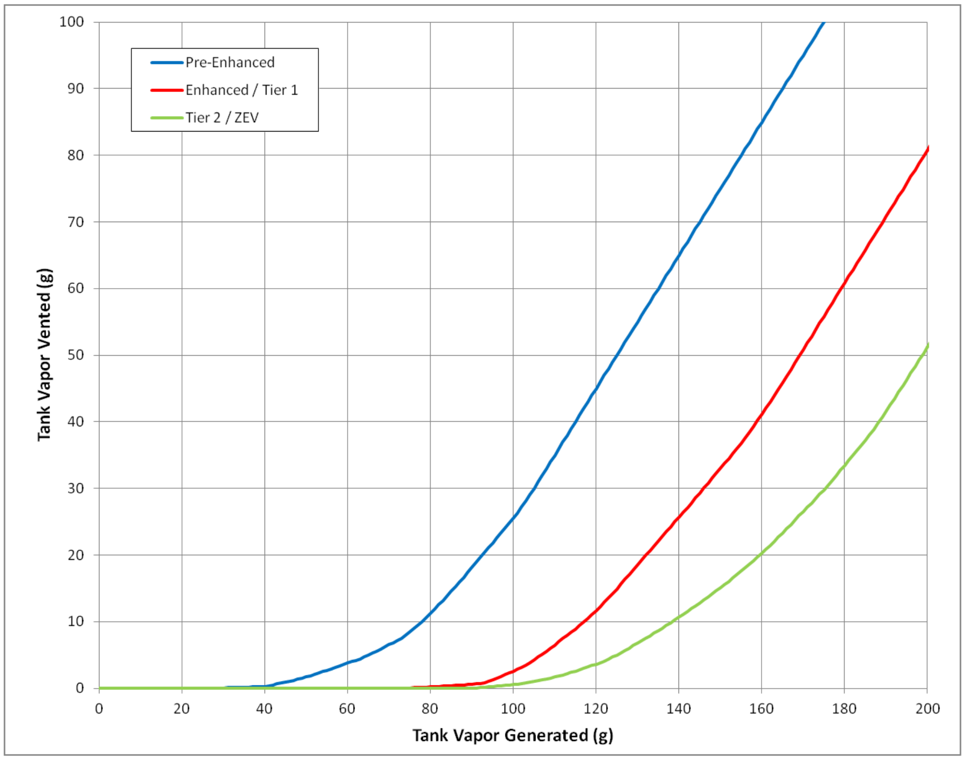
Model / ID	Weighting Factor	Canister Size
7001	0.0435	20
7006	0.0435	30
7015	0.0435	153
7033	0.0435	40
7046	0.0435	82
7088	0.0435	121
7091	0.0435	142
7131	0.0435	98
7150	0.0435	49
7461	0.0435	115
7463	0.0435	100
7476	0.0435	40
7508	0.0435	121
7551	0.0435	80
7556	0.0435	163
7562	0.0435	90
7667	0.0435	50
7672	0.0435	60
7703	0.0435	100
7713	0.0435	163
7753	0.0435	80
7794	0.0435	62
7859	0.0435	40

Table 3 - Tier 2+ / ZEV DELTA Model Inputs

Model / ID	Weighting Factor	Canister Size
7059	0.05556	161
7099	0.05556	172
7130	0.05556	121
7142	0.05556	153
7170	0.05556	121
7197	0.05556	172
7229	0.05556	90
7289	0.05556	153
7252	0.05556	70
7429	0.05556	200
7462	0.05556	40
7516	0.05556	203
7531	0.05556	100
7725	0.05556	60
7803	0.05556	203
7558	0.05556	40
7696	0.05556	120
7871	0.05556	120

The DELTA model was run three times, using each of the above tables as a set of individual vehicle inputs. The model was run for a temperature range of 65-105F, an altitude of sea level (14.7psi) and a fuel RVP of 10psi. The resulting TVG – TVV curves produced by the DELTA model can be seen in Figure 12 below.

Figure 12 - DELTA Model Results for Pre-Enhanced, Enhanced and Tier 2 Fleet Averages

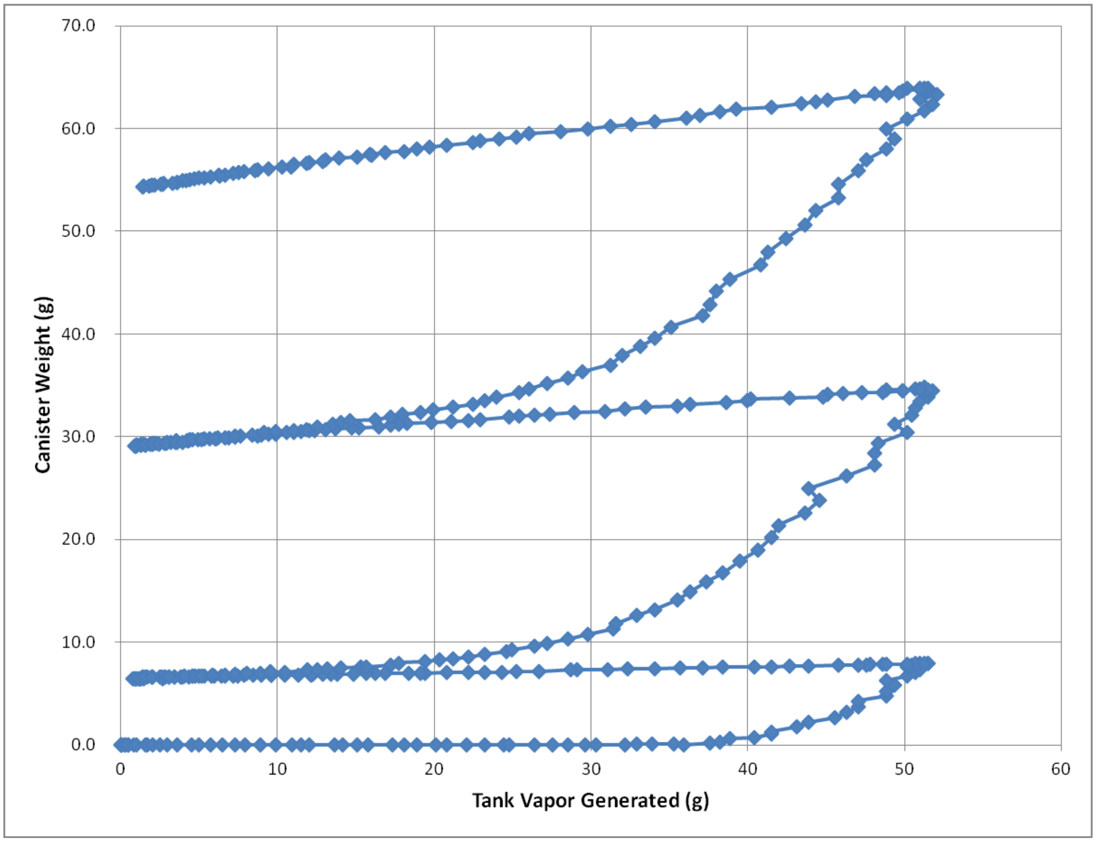


Note that diurnal temperature, altitude and fuel RVP do not affect the shape of the TVG – TVV curves, only the output from those curves. Although the values for these variables in the model have been selected to most closely match those found in the E77 vehicle data; a comparison using the TVG – TVV curves as a basis should not be affected by changes in these inputs (as changes would only impact TVG itself, not the relationship between TVG and TVV).

b. Comparison to E77 vehicle fleets

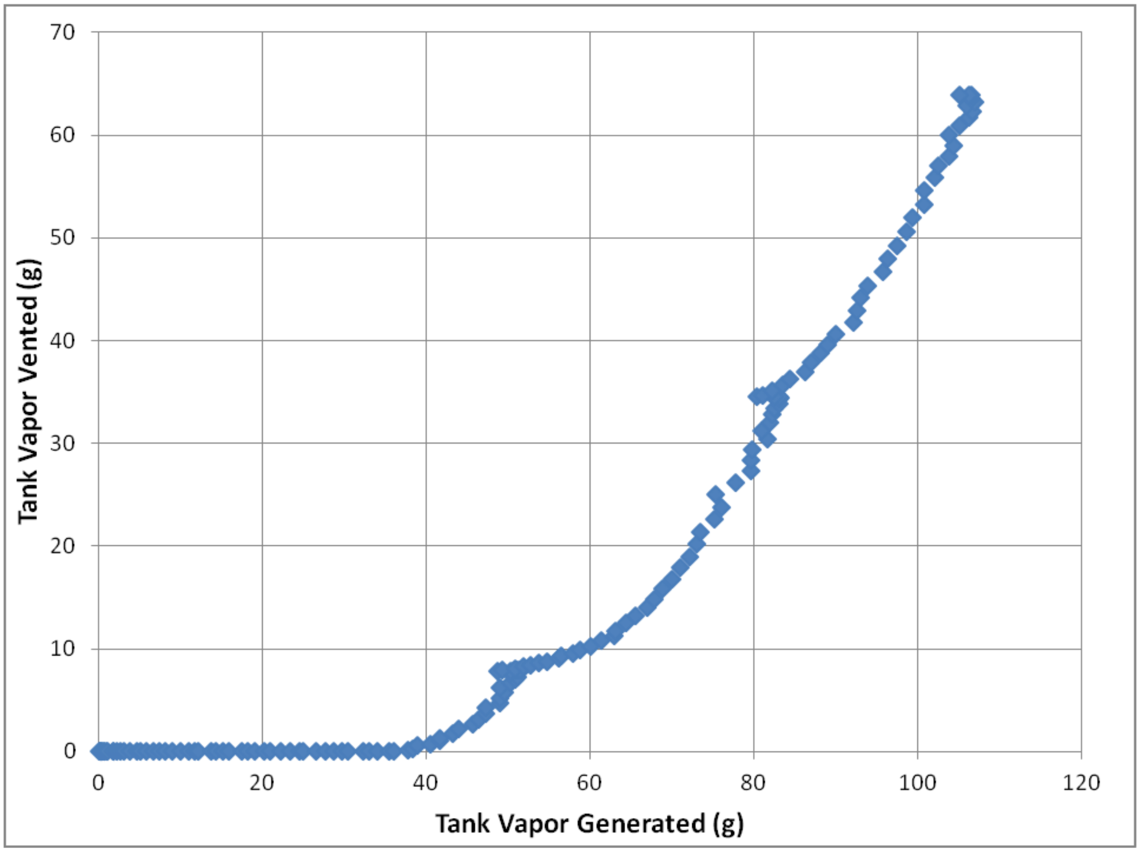
The E77 vehicle fleet data was first reconstructed in a form that is easily comparable to the TVG – TVV curves produced by the DELTA model. The data from E77 was originally of the form: total canister breakthrough weight vs. time (specifics on how this data was obtained, including detailed descriptions of the test setup can be found in the E77 report). This data includes backpurge events and a dependence on temperature that is not useful for comparison with the TVG – TVV curves produced by the DELTA model. An example of the original E77 data can be seen in Figure 13 below.

Figure 13 - Untransformed E77 Vehicle Breakthrough Data



The Wade-Reddy equation was used to approximate the amount of vapor generation for every point in the original E77 data since the altitude, fuel RVP, and temperature of the emissions shed were known for all datapoints. Using the results from the Wade-Reddy equation as the TVG for the E77 data, the canister breakthrough weight was then reconstructed to represent the TVV for that vehicle. Firstly, the portions of canister breakthrough weight data that occurred during diurnal cooling (the backpurge events) were removed. Secondly, the portions of canister breakthrough weight data that occurred during diurnal heating were shifted to fill the gaps formed by the removal of the diurnal cooling data. Finally, the remaining portions of the canister breakthough weight data were matched with the proper TVG point based on the temperature of the shed at the time they were recorded. This process creates a TVG – TVV curve that is comparable to the TVG – TVV curve produced by the DELTA model, as seen in Figure 14 below.

Figure 14 - Transformed E77 Vehicle Breakthrough Data



Note the above figure represents the reconstructed version of the original E77 data for the vehicle shown previously in Figure 14. A script carrying out the process described above automatically can be found in Appendix B to this document.

By applying this reconstruction process to every vehicle in the E77 fleet, a cloud of TVG – TVV points was generated for each subset of E77 vehicles: pre-enhanced, enhanced/Tier 1, and Tier 2 (each characteristic rise in TVV seen in the following plots represents one set of vehicle test data). These point clouds were then compared to the TVG – TVV lines generated by the DELTA model. These comparisons are seen in the following figures.

Figure 15 - Pre-enhanced E77 / DELTA Model Comparison

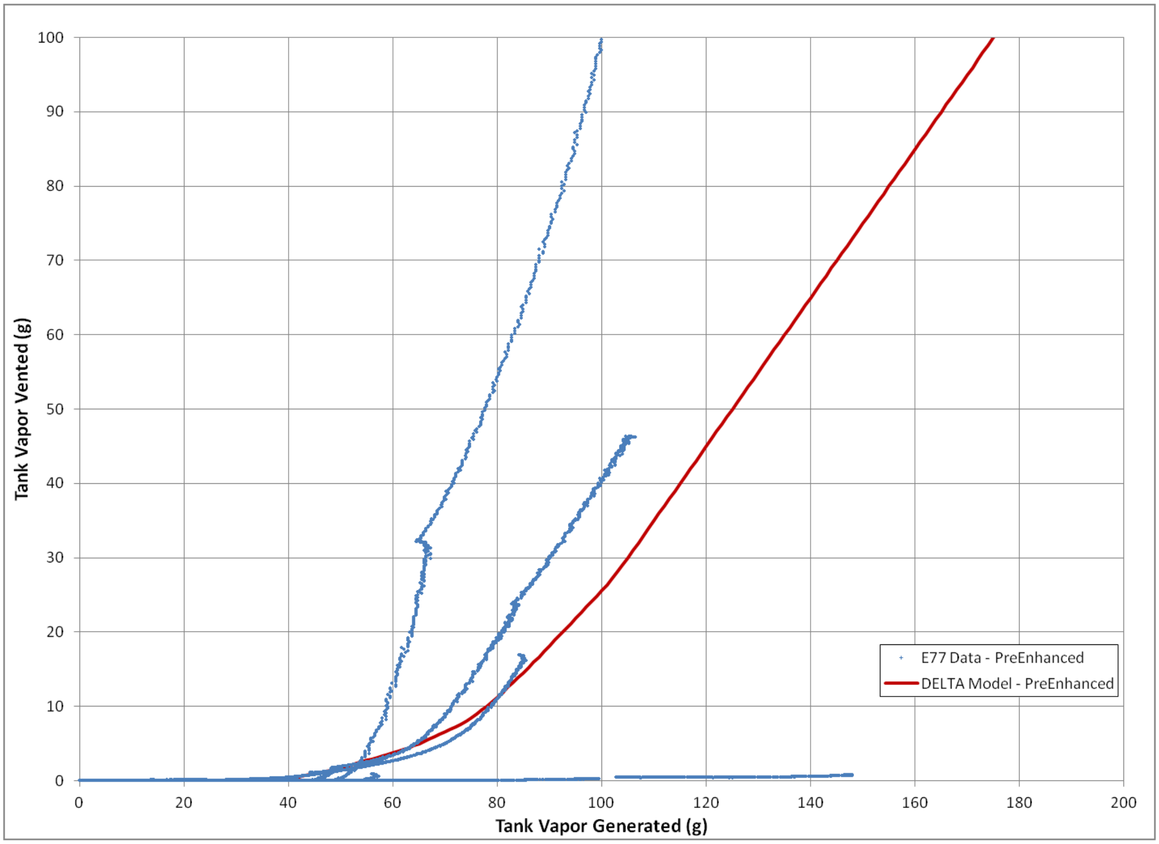


Figure 16 - Enhanced/Tier 1 E77 / DELTA Model Comparison

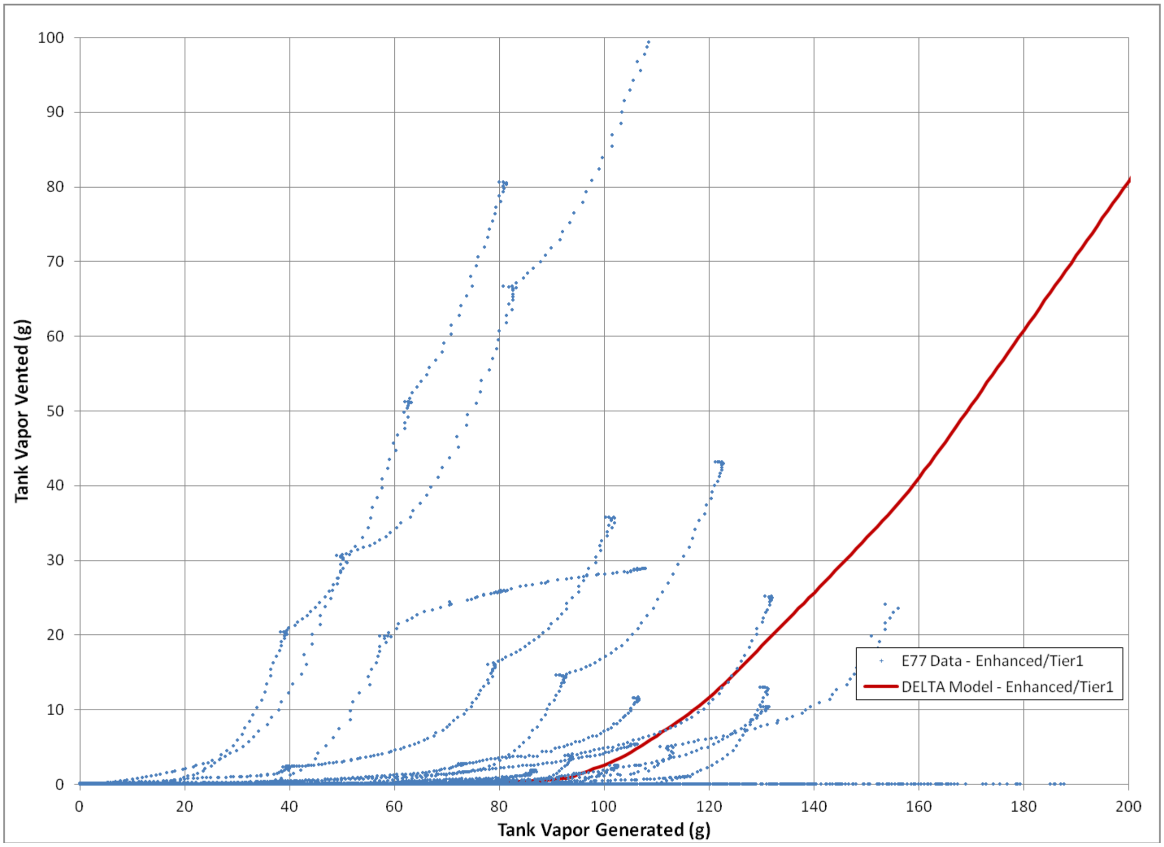
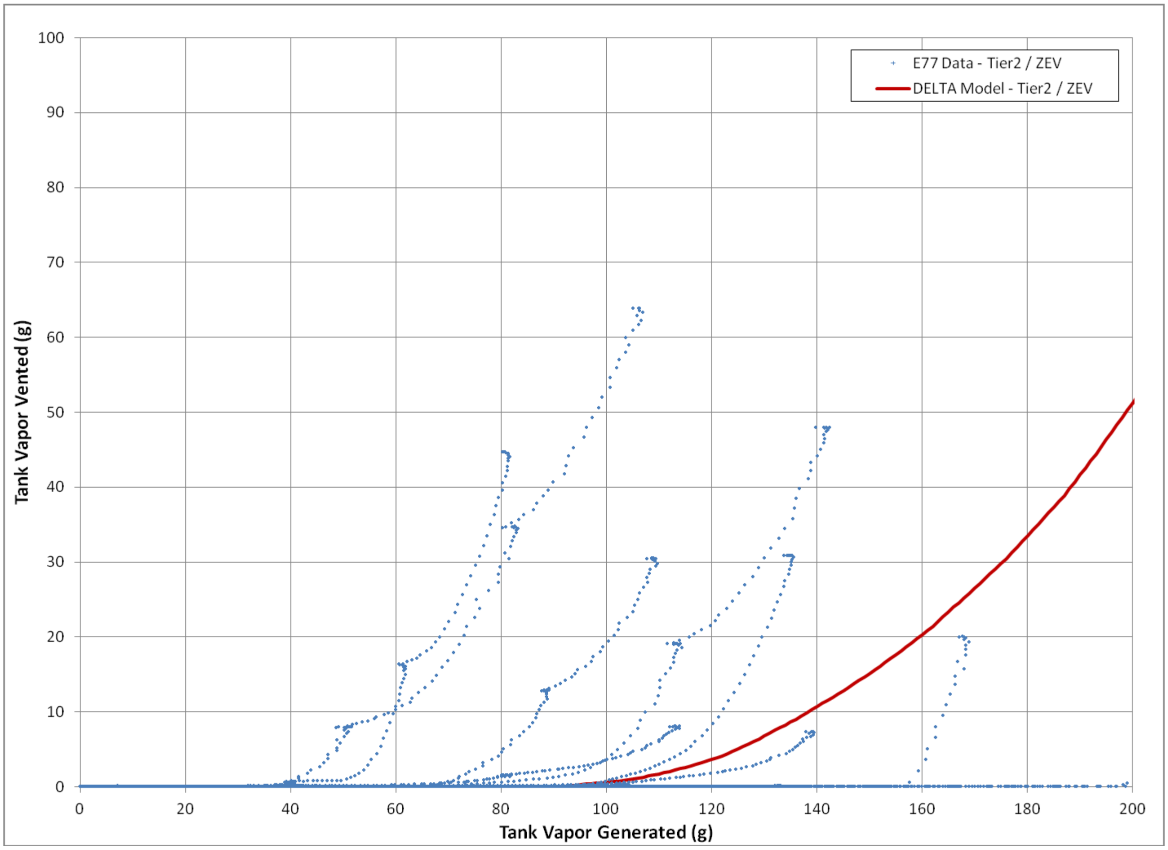


Figure 17 - Tier 2/ZEV E77 / DELTA Model Comparison



From the figures above it was apparent that the DELTA model based on ideal canister size was under-predicting breakthrough emissions for all but a few cases of the E77 vehicles. A discussion of these results can be found in the next subsection.

c. Discussion of non-ideal canister behavior in the E77 vehicle fleet

The comparisons shown by the figures in the previous subsection indicate a large under-prediction of breakthrough emissions when using the DELTA model based on ideal canister capacities and canister behavior. A more thorough analysis of E77 vehicle breakthrough was completed to explain the differences seen between the ideal model and what was happening in real world testing. It is important to note that the preconditioning procedure performed on the E77 vehicles to ensure adequate purge between tests, while meant to emulate a standard FTP cycle, was performed on public roads with variable weather conditions. This real-world preconditioning may have contributed to the non-ideal behavior seen in the data. For each test conducted in the E77 multi-day diurnal study, the canister breakthrough point (which was determined as the point at which more than 2% of the total canister capacity had escaped the vehicle canister) was compared against the theoretical capacity for the canister on that particular vehicle. The results of this analysis are shown in the following tables, separated by certification class.

Table 4 - E77 Tier2/ZEV Premature Breakthrough

Test #	Veh #	Fuel RVP (psi nominal)	Breakthrough Point (g)	Canister Capacity (g)	Difference (g)	% of Rated Capacity
7059	212	10	161	172	-11.05	93.58%
7099	212	9	135	172	-37.05	78.47%
7130	211	9	132	121	11	109.09%
7142	215	10	171	153	17.55	111.44%
7170	211	10	90	121	-30.9	74.44%
7197	212	9	139	172	-33.05	80.79%
7229	215	9	90	153	-63.45	58.65%
7289	215	9	136	153	-17	88.89%
7252	211	9	70	121	-50.9	57.90%
7429	213	10	200	203	-2.74	98.65%
7462	210	10	40	115	-75.32	34.69%
7516	213	9	222	203	19.26	109.50%
7531	210	9	100	115	-15.32	86.72%
7725	210	9	60	115	-55.32	52.03%
7803	213	9	237	203	34.26	116.90%

Table 5 - E77 Enhanced/Tier 1 Premature Breakthrough

Test #	Veh #	Fuel RVP (psi nominal)	Breakthrough Point (g)	Canister Capacity (g)	Difference (g)	% of Rated Capacity
7001	205	10	20	107	-87.0	18.70%
7006	204	10	30	121	-90.9	24.81%
7015	207	10	194	153	40.6	126.43%
7033	204	9	40	121	-80.9	33.09%
7046	205	9	82	107	-25.0	76.67%
7088	204	9	128	121	7.1	105.87%
7091	207	9	142	153	-11.5	92.54%
7131	205	9	98	107	-9.0	91.63%
7150	207	9	49	153	-104.5	31.93%
7461	209	10	115	121	-5.9	95.12%
7463	208	10	100	163	-62.8	61.44%
7476	206	10	40	112	-71.6	35.84%
7508	209	9	128	121	7.1	105.87%
7551	206	9	80	112	-31.6	71.68%
7556	208	9	129	163	-33.8	79.26%
7562	221	10	90	153	-63.5	58.65%
7667	221	9	50	153	-103.5	32.58%
7672	207	10	60	153	-93.5	39.10%
7703	206	9	100	112	-11.6	89.61%
7713	208	9	142	163	-20.8	87.25%
7753	209	9	80	121	-40.9	66.17%
7794	207	10	62	153	-91.5	40.40%
7859	221	9	40	153	-113.5	26.07%

Premature breakthrough occurred in tests at a wide range of ambient lab temperatures and humidity. Note that although the tests occurred in a controlled evaporative SHED, preconditioning occurred on surface streets meant to emulate an FTP dynamometer cycle where ambient conditions could affect the state of the canister. Premature breakthrough occurred at levels as low as 19% of the ideal canister capacity for a vehicle, with the average vehicle breakthrough occurring at 72% of ideal canister capacity. The under-estimation of fleet breakthrough emissions is due to the fact that the DELTA model is reliant on ideal canister capacity for breakthrough calculations; because the fleet performed at only 72% of ideal canister capacity, the DELTA model cannot properly account for the non-ideal behavior. A method of correcting the DELTA model to more correctly reflect the non-ideal behavior of a real-world fleet follows in the next section.

VI. Correcting DELTA for non-ideal behavior

As described in the previous section, the data from the E77 program shows that evaporative emission control systems on many vehicles are not operating as an ideal model would predict. EPA believes there are a number of reasons why this non-ideal behavior may be occurring. While evaporative emission canister technology is relatively simple, deterioration of the charcoal in the canister can occur for a variety of reasons including if the canister is exposed to liquid or repeated dusty conditions. This type of deterioration could result in permanent reduction in vapor storage capacity of the canister. In addition, canisters in the real-world may not experience as much purge as canisters tested under the certification procedures. While the vehicles tested in the E77 program were prepped for testing by driving under real-world operation meant to simulate certification pre-conditioning, it appears that some of the canisters may not have been purged by the real-world operation as much as canisters prepped in the laboratory that are following the certification procedures. Lower purge levels in the real-world could lead to temporary reduction in vapor storage capacity until the vehicles are driven for sufficient distances to purge the canister more completely.

To address the fact that the E77 program results show some evaporative emission control systems do not operate ideally, EPA developed a modified approach for modeling evaporative emissions in the DELTA model. This modified approach relies on the basic relationship between tank vapors vented (TVV) and tank vapors generated (TVG) upon which the DELTA model is based, as shown below.

$$TVV = TVG – \text{(theoretical capacity)}$$

For the purposes of this analysis, the theoretical capacity of the evaporative emission canister replaces the real-world capacity of the evaporative emission canister. Table 4 and

Table 5, presented earlier, contain the estimated real-world capacity of the evaporative emission canisters for each of the Tier 1 and Tier 2 vehicles tested in the E77 program. The following equation shows the modified relationship between the TVV and TVG terms.

TVV = TVG – (real-world capacity)

It should be noted that TVV will be zero if TVG is less than or equal to the real-world capacity of the evaporative emission canister.

Because vehicles have a variety of canister capacities, and the E77 program results show that many vehicles experience breakthrough of the evaporative emission canisters at less than the theoretical working capacity, EPA decided to use the equation noted above and develop a modified approach for the whole vehicle fleet that would attempt to factor in both of these conditions into the modeling. The following sections describe the development of the equations used in the DELTA model for the Tier 2 and Tier 1 vehicle fleets based on the E77 program results. EPA's approach for modeling pre-enhanced vehicles in the DELTA model is presented as well.

a. Tier 2 vehicles

The first step in this approach was to divide the modified equation by TVG. This results in the following equation:

TVV/TVG = 1 – (real-world capacity)/TVG

Next, the "real-world capacity" term in the equation was replaced by a new term equal to the real-world fraction of theoretical capacity multiplied by the theoretical canister capacity. For example, as noted in Table 4, test number 7099 on vehicle number 212 in the E77 program had a real-world capacity of approximately 135 grams and a theoretical capacity of 172 grams. Therefore, the real-world fraction of theoretical capacity would be 0.785 (i.e., 135 grams divided by 172 grams). The equation with the replaced term is as follows:

TVV/TVG = 1–[(real-world fraction of theoretical capacity)*(theoretical capacity)]/TVG

This equation can be rearranged as follows:

TVV/TVG = 1 – (real-world fraction of theoretical capacity)/(TVG/theoretical capacity)

This equation can be represented as follows for graphing purposes where the y-axis represents (TVV/TVG) and the x-axis represents (TVG/theoretical capacity):

y = 1 – (real-world fraction of theoretical capacity)/x

Putting the equation in this rearranged form "normalizes" the emission results on TVG/theoretical capacity and allows each test/vehicle combination from the E77 program to be compared on the same basis. This rearrangement also removes the impact of the differences in theoretical capacity and real-world capacity which exist for each test/vehicle combination that would otherwise occur in any comparison of TVV and TVG. Based on this equation, a graph was be made for each test/vehicle combination in the E77 program by calculating and graphing TVV/TVG (on the y-axis) as a function of TVG/theoretical capacity (on the x-axis). (It should be noted that the TVV/TVG value is zero if TVG/theoretical capacity is less than or equal to the real-world fraction of theoretical capacity.)

Figure 18 presents this relationship for one test/vehicle combination from the E77 program for test 7099 on vehicle 212, which is a Tier 2 vehicle. For this test/vehicle combination, canister breakthrough occurred at 0.785 of the theoretical capacity of the canister. At that point, the ratio of TVV/TVG rises as TVG/theoretical capacity increases. All such graphs asymptotically approach a TVV/TVG value of 1.00 as the value of TVG/theoretical capacity increases to higher and higher levels.

Figure 18 - Graph for Test 7099/Vehicle 212

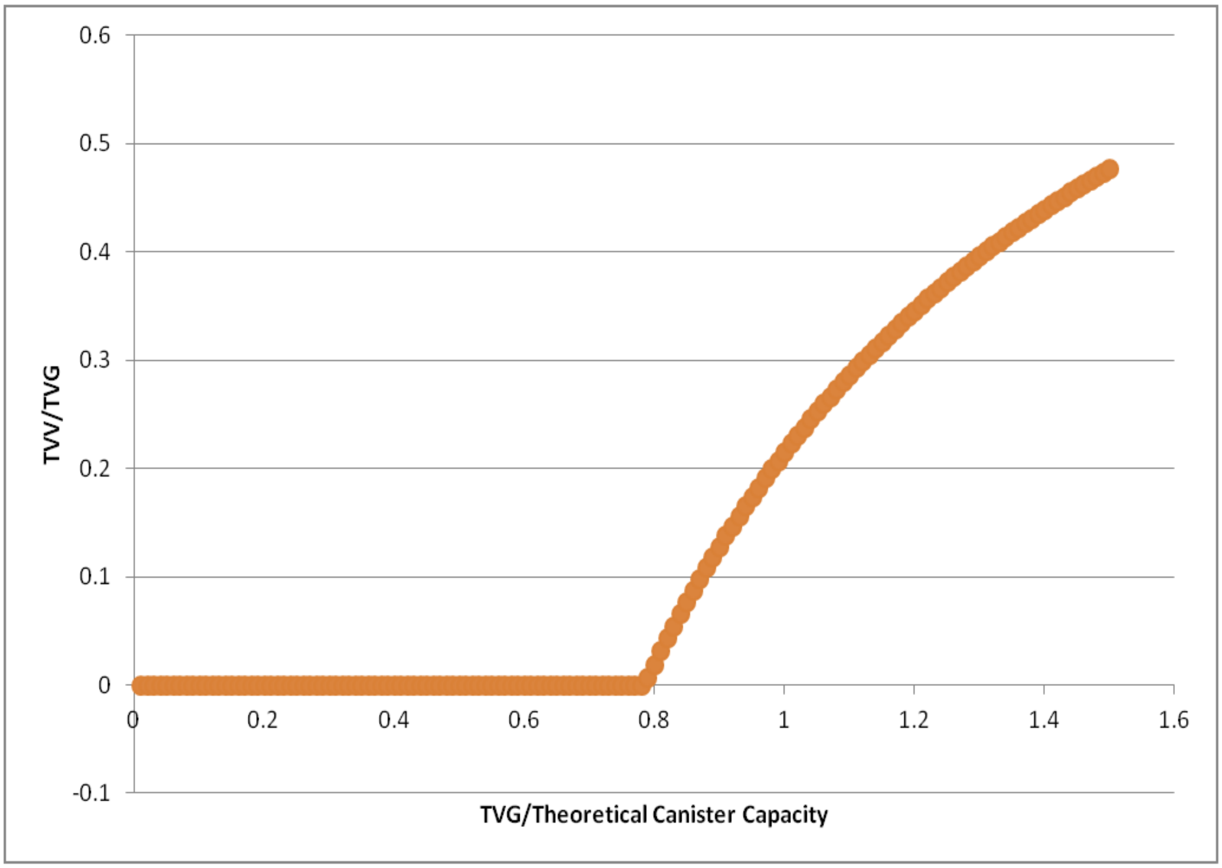
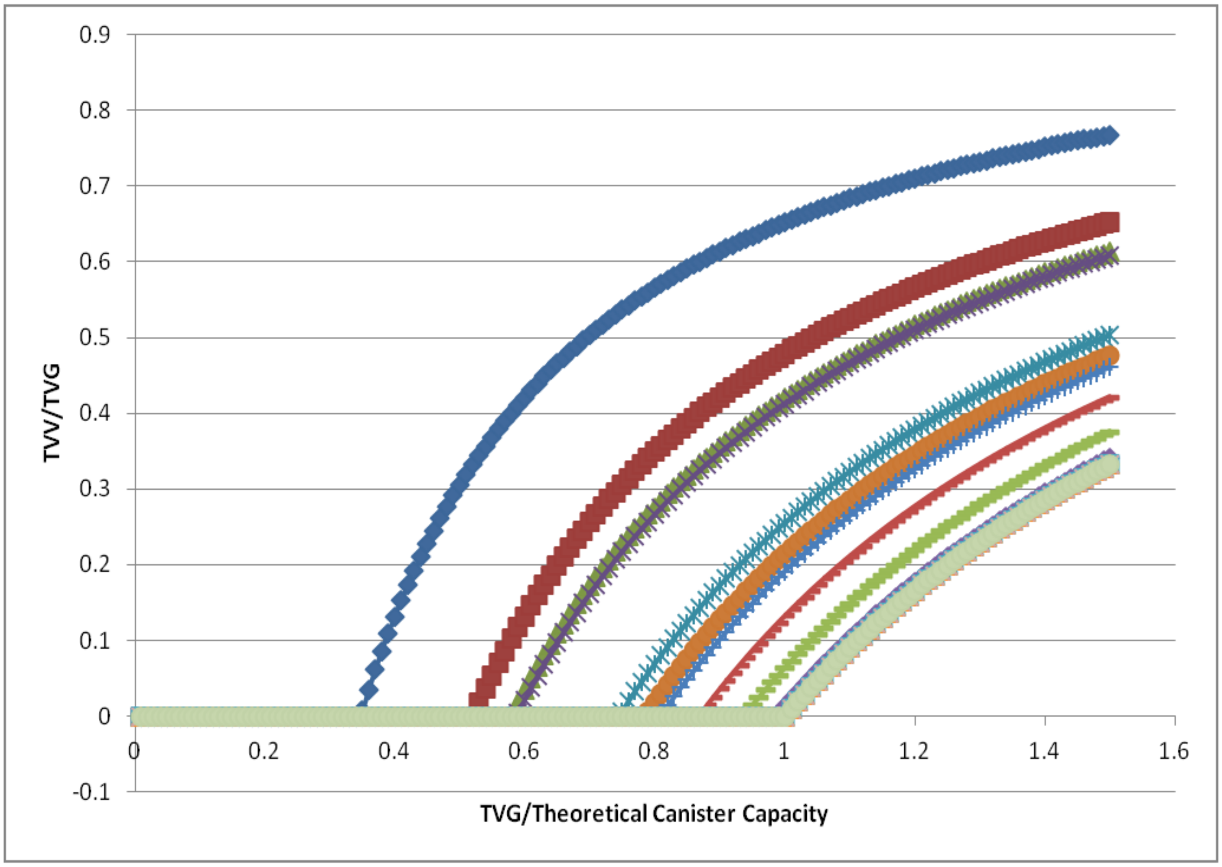


Figure 19 shows the results for all 15 test/vehicle combinations for Tier 2 vehicles in the E77 program (as presented in Table 5). For the E77 program, there were five Tier 2 vehicles tested, with three different tests performed on each vehicle with different fuels, resulting in 15 test/vehicle combinations. Of the 15 test/vehicle combinations, breakthrough occurred earlier than the theoretical canister capacity would suggest on 10 of the test/vehicle combinations. The remaining 5 test/vehicle combinations that behaved ideally (i.e., breakthrough occurred at or above the theoretical canister capacity) are shown in Figure 19 with curves that start to increase at a value of 1.0 for TVG/theoretical canister capacity.

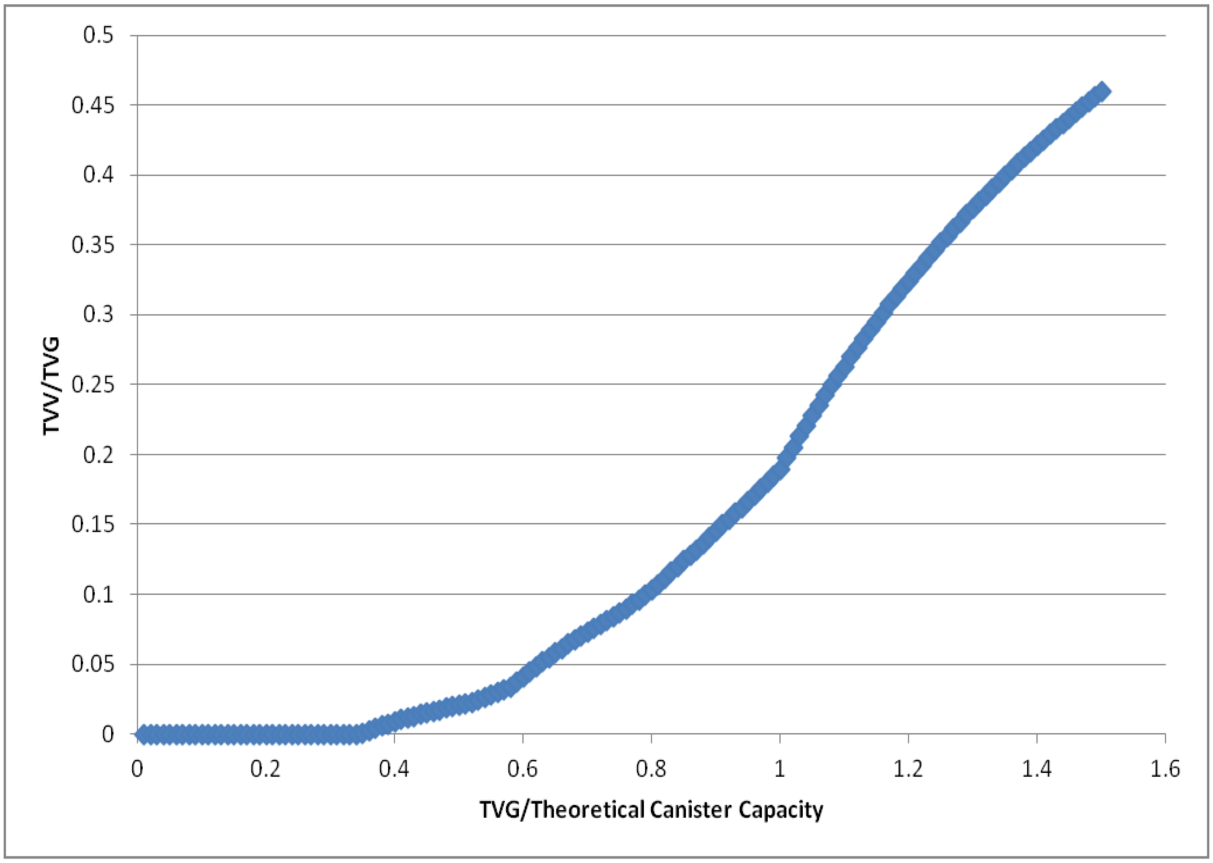
Figure 19 - Graphs for All Tier 2 Vehicles



Based on the results for each of the test/vehicle combinations from the E77 program, the TVV/TVG values were averaged across all 15 test/vehicle combinations to result in a single graph representing all of the Tier 2 vehicles. EPA is using the Tier 2 vehicle dataset from the E77 program as a representation of the entire Tier 2 vehicle fleet

Figure 20 shows the resulting average graph of all test/vehicle combinations for Tier 2 vehicles from the E77 program.

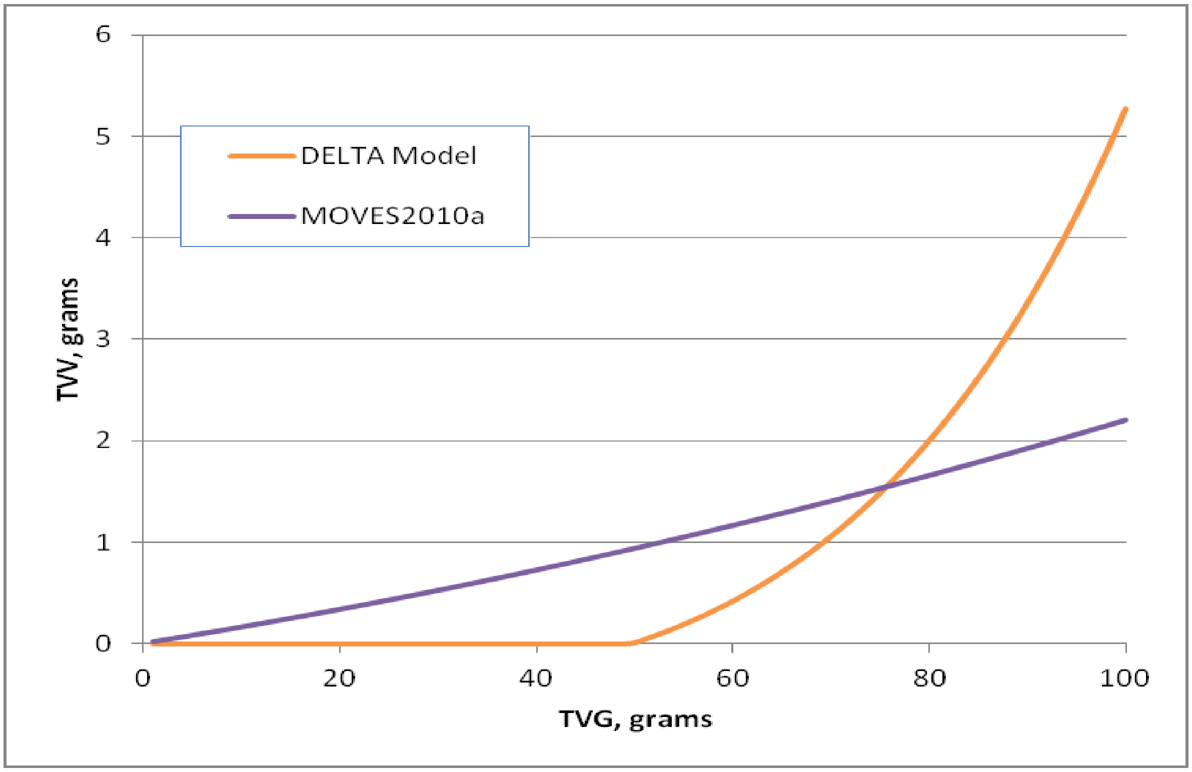
Figure 20 - Average Tier 2 Vehicle Graph



This average curve for Tier 2 vehicles was then converted back into the form needed for the DELTA model of TVV versus TVG. First, the x-axis values were multiplied by the average theoretical canister capacity of the Tier 2 vehicles tested in the E77 program to obtain TVG values. The average theoretical canister capacity value was determined to be 152.8 grams, a value slightly higher than Tier 2 vehicles certified with EPA which averaged from approximately 136 to 150 grams over model years 2004 through 2010. Next, the y-axis values were multiplied by the associated TVG values at each point (as determined in the first step) to obtain TVV values. Figure XX shows the resulting TVV (on the y-axis) versus TVG (on the x-axis) curve for the Tier 2 fleet for the DELTA model.

Figure 21 also shows the TVV versus TVG curve as it currently exists in the MOVES2010a model for Tier 2 vehicle.

Figure 21 - TVV versus TVG for Tier 2 Fleet



The x and y values from the resulting graph of TVV versus TVG for the Tier 2 fleet were then curve-fit based on an equation of the following form in order to provide inputs for the DELTA model:

$$y = \frac{-(Bx + E) \pm \sqrt{(Bx + E)^2 - 4C(Ax^2 + Dx + F)}}{2C}$$

Table 6 shows the values of the constants determined for the equation based on the curve-fit analysis of the TVV versus TVG curve for the Tier 2 fleet.

Table 6 - Modeling Inputs for Tier 2 Vehicles

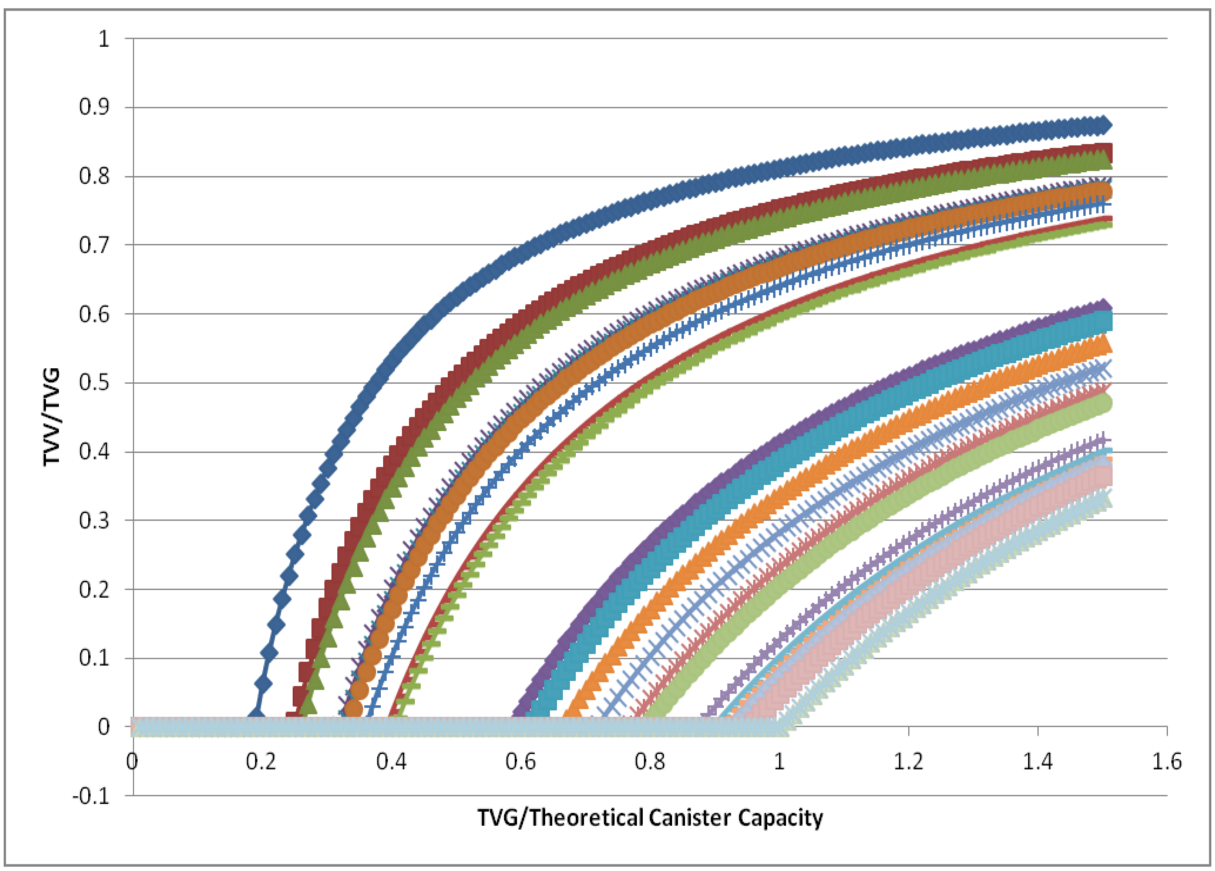
Constant	Value for the Tier 2 Fleet
A	-0.071
B	-1.20
C	1.15
D	3.12
E	187
F	20

b. Enhanced/Tier 1 vehicles

For Enhanced/Tier 1 vehicles, EPA followed a similar approach to that described above for deriving the equations used for modeling evaporative emissions with the DELTA model.

Table 4 shows the breakthrough points for the test/vehicle combinations from the E77 program for Enhanced/Tier 1 vehicles. For the E77 program, there were seven Enhanced/Tier 1 vehicles tested, with three different tests performed on each vehicle with different fuels plus an additional two tests on one of the vehicles, resulting in 23 test/vehicle combinations.
Figure 22 presents the TVV/TVG versus TVG/theoretical capacity results for all 23 test/vehicle combinations for Enhanced/Tier 1 vehicles in the E77 program. Of the 23 test/vehicle combinations, breakthrough occurred earlier than the theoretical canister capacity would suggest on 20 of the test/vehicle combinations. The remaining 3 test/vehicle combinations that behaved ideally (i.e., breakthrough occurred at or above the theoretical canister capacity) are shown in Figure 22 with curves that start to increase at a value of 1.0 for TVG/theoretical canister capacity.

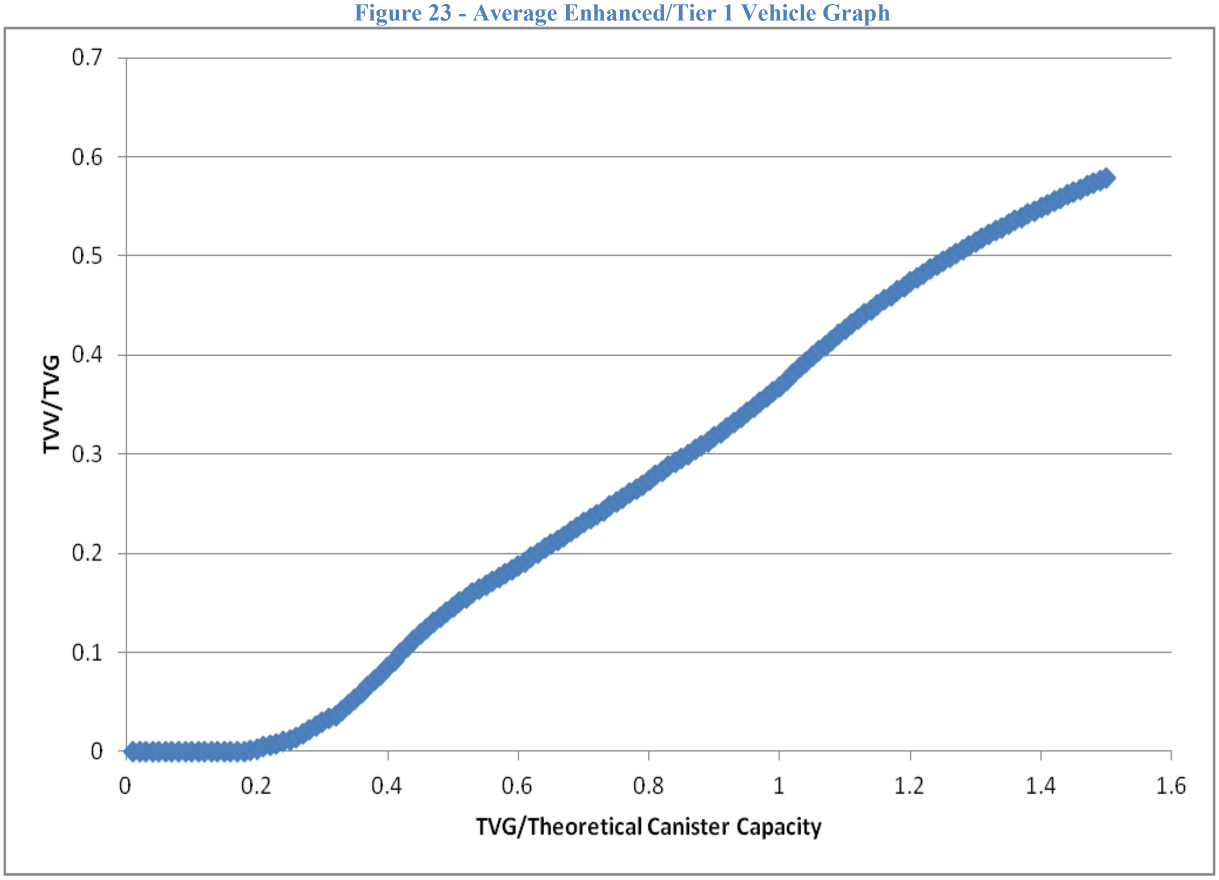
Figure 22 - Graphs for All Enhanced/Tier 1 Vehicles



Based on the results for each of the test/vehicle combinations from the E77 program, the TVV/TVG values were averaged across all 23 test/vehicle combinations to result in a single graph representing all of the Enhanced/Tier 1 vehicles. EPA is using the Enhanced/Tier 1 vehicle dataset from the E77 program as a representation of the entire Enhanced/Tier 1 vehicle fleet.

Figure 23 shows the resulting average graph of all test/vehicle combinations for Enhanced/Tier 1 vehicles from the E77 program.

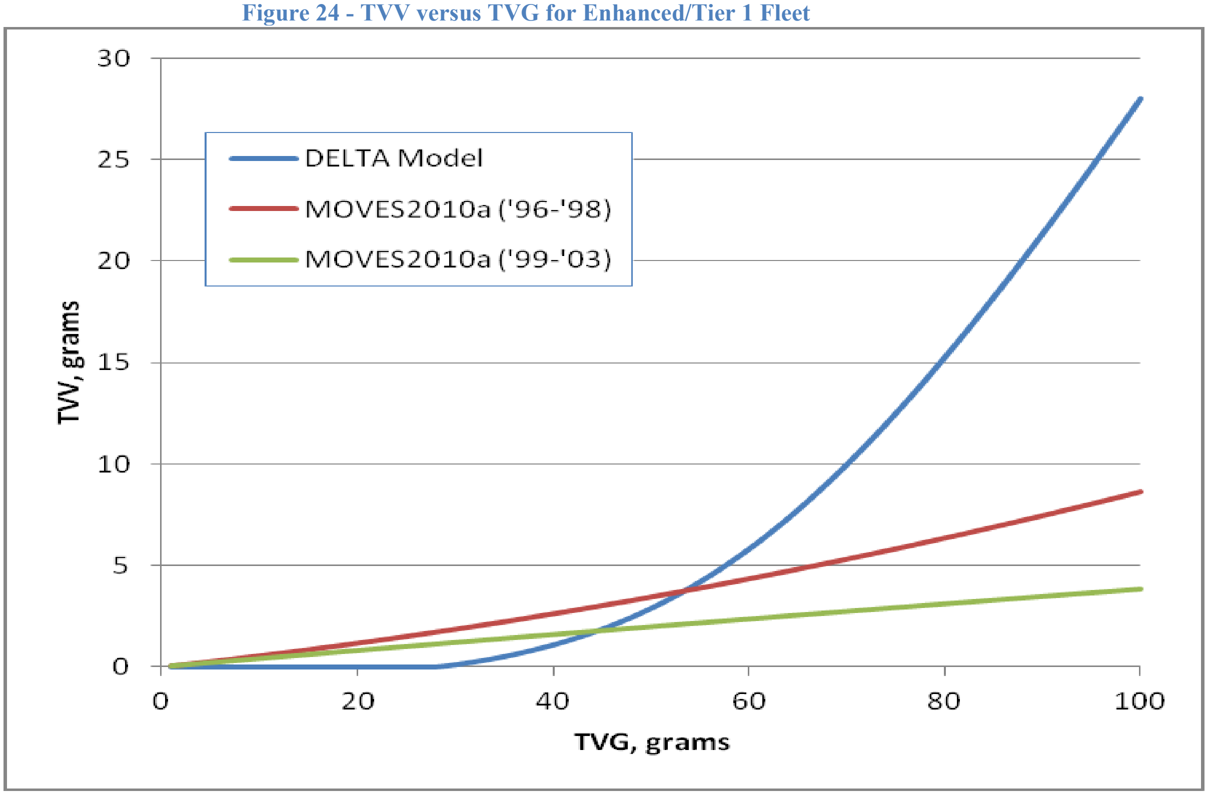
Figure 23 - Average Enhanced/Tier 1 Vehicle Graph



This average curve for Enhanced/Tier 1 vehicles was then converted back into the form needed for the DELTA model of TVV versus TVG. First, the x-axis values were multiplied by the average theoretical canister capacity of the Enhanced/Tier 1 vehicles tested in the E77 program to obtain TVG values. The average theoretical canister capacity value was determined to be 134.6 grams, a value slightly higher than the estimated average of Enhanced/Tier 1 vehicles certified with EPA between model year 1999 and 2003 of approximately 123 grams. Next, the y-axis values were multiplied by the associated TVG values at each point (as determined in the first step) to obtain TVV values.

Figure 24 shows the TVV versus TVG curve as it currently exists in the MOVES2010a model for Enhanced/Tier 1 vehicles. It also shows the resulting TVV (on the y-axis) versus TVG (on the x-axis) curve for the Enhanced/Tier 1 fleet for the DELTA model.

Figure 24 - TVV versus TVG for Enhanced/Tier 1 Fleet



The x and y values from the resulting graph of TVV versus TVG for the Tier 1 fleet were then curve-fit based on an equation of the following form in order to provide inputs for the DELTA model:

$$y = \frac{-(Bx + E) \pm \sqrt{(Bx + E)^2 - 4C(Ax^2 + Dx + F)}}{2C}$$

Table 7 shows the values of the constants determined for the equation based on the curve-fit analysis of the TVV versus TVG curve for the Tier 1 fleet.

Table 7 - Modeling Inputs for Enhanced/Tier 1 Vehicles

Constant	Value for the Enhanced/Tier 1 Fleet
A	-0.125
B	-1.34
C	1.90
D	2.70
E	115
F	23

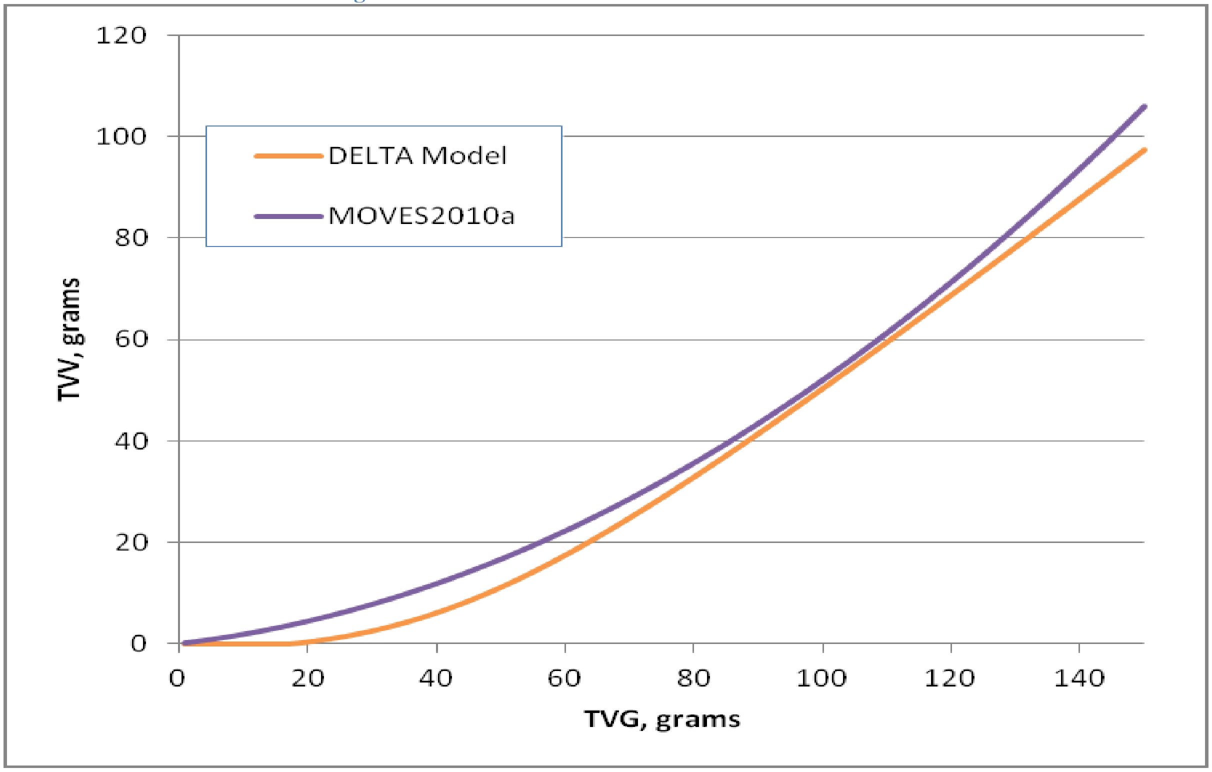
c. Pre-enhanced vehicles

For pre-enhanced vehicles, EPA did not collect any emissions data in the E77 program. Because the basic technologies use on pre-enhanced vehicles to control evaporative emissions are similar to those used on Enhanced/Tier 1 vehicles and Tier 2 vehicles, we believe the same type of issues such as canister deterioration and limited purge would result in similar evaporative emission trends as those found on vehicles tested in the E77 program. For the purposes of this analysis, we believe that pre-enhanced vehicles would have a similarly shaped curve of TVV/TVG versus TVG/theoretical capacity as Enhanced/Tier 1 vehicles because their evaporative emission control systems are closer in design to those of Enhanced/Tier 1 vehicles.

Based on the average curve of TVV/TVG versus TVG/theoretical capacity for Enhanced/Tier 1 vehicles, EPA converted the values back into the form needed for the DELTA model of TVV versus TVG as described earlier. First, the x-axis values were multiplied by the average theoretical canister capacity of pre-enhanced vehicles certified with EPA to obtain TVG values. The average theoretical canister capacity value was determined to be 72.8 grams for vehicles certified with EPA between model year 1978 and 1995. Next, the y-axis values were multiplied by the associated TVG values at each point (as determined in the first step) to obtain TVV values.

Figure 25 shows the resulting TVV (on the y-axis) versus TVG (on the x-axis) curve for the pre-enhanced fleet for the DELTA model. It also shows the TVV versus TVG curve as it currently exists in the MOVES2010a model for Pre-Enhanced vehicles.

Figure 25 - TVV versus TVG for Pre-Enhanced Fleet



The x and y values from the resulting graph of TVV versus TVG for the pre-enhanced fleet were then curve-fit based on an equation of the following form in order to provide inputs for the DELTA model:

$$y = \frac{-(Bx + E) \pm \sqrt{(Bx + E)^2 - 4C(Ax^2 + Dx + F)}}{2C}$$

Table 8 shows the values of the constants determined for the equation based on the curve-fit analysis of the TVV versus TVG curve for the pre-enhanced vehicle fleet.

Table 8 - Modeling Inputs for Pre-Enhanced Vehicles

Constant	Value for the Pre-Enhanced Vehicle Fleet
A	-0.25
B	-1.00
C	1.25
D	0.2
E	85
F	70