sierra research

Report No. SR2005-07-01

# Review of MOVES2004

prepared for:

## Alliance of Automobile Manufacturers

July 15, 2005

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# REVIEW OF MOVES2004

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# 1. EXECUTIVE SUMMARY

For over 25 years, the U.S. EPA has used the MOBILE series of emission factor models to estimate on-road motor vehicle emissions. The MOBILE models have formed the basis for the development of state implementation plans (SIPs) demonstrating how compliance with National Ambient Air Quality Standards will be achieved and for demonstrating transportation plan conformity. The latest version of the MOBILE series of models, MOBILE6.2, was released by EPA in November 2003.

In response to criticism of the MOBILE series of models, as well as the perceived need to expand the tools available for estimating emissions, EPA has spent several years developing a replacement model. This replacement model, known as "MOVES" (MOtor Vehicle Emissions Simulator), embodies significant methodology changes in the way on-road motor vehicle emissions are estimated as it uses a "modal," rather than the drive-cycle based approach used in the MOBILE series of models.

The first public version of the model, MOVES2004, which was released in January 2005, estimates on-road motor vehicle energy consumption as well as emissions of methane ($CH_4$) and nitrous oxide ($N_2O$), but does not generate estimates of criteria pollutant emissions (e.g., VOC, CO, NOx, PM, and SOx). Although MOVES2004 does not generate estimates of criteria pollutants, EPA has made it clear that subsequent versions of MOVES will use the same basic methodologies embodied in MOVES2004 to estimate criteria pollutant emissions from on-road motor vehicles and that the MOVES series of models will replace the MOBILE series of models for use in control measure assessments and SIP preparation.

Given the implications that MOVES presents for the automobile industry and EPA's request for public comment on MOVES2004, the Alliance of Automobile Manufacturers commissioned Sierra Research, Inc. and Air Improvement Resource to conduct a review of the MOVES2004 model primarily as it relates to passenger cars and light-duty trucks.

While the results of this review are quite technical the following general findings were made:

1. MOVES2004 appears to generate fairly reasonable overall estimates of fuel consumption for the existing vehicle fleet. However, it is not clear that this result is due to the accuracy of the model in predicting those emissions rather than the existence of compensating errors. In addition, there are areas of vehicle

operation, such as high speed and load conditions where additional data need to be developed and incorporated into the database underlying MOVES2004.

2. MOVES2004 does not appear to be capable of generating reasonable overall estimates of fuel consumption from the future vehicle fleet as the component of the model used to account for future technologies (known as the Physical Emission Rater Estimator or PERE model) is fundamentally flawed. PERE should not estimate uniform improvement over the full range of engine operation, and it has erroneous assumptions with modeling hybrid technology operation. Given the fact that modeling $CO_2$ emissions with a physical model such as PERE is much more straightforward than modeling criteria pollutant emissions, significant uncertainty will be introduced if an attempt is made to revise PERE to model criteria pollutants.

3. The methodology used by MOVES2004 to predict emissions of methane and nitrous oxide from the existing vehicle fleet needs to be modified to improve the accuracy of those predictions. In particular, estimates of $N_2O$ emissions should be made for Tier 2 vehicles, which are subject to more stringent NOx standards than are the LEV I vehicles upon which the $N_2O$ emissions were based. In addition, EPA should check to ensure that it has not combined tests where high- and low-sulfur fuels were used, and should develop sulfur correction factors for both $CH_4$ and $N_2O$ and apply those correction factors in MOVES2004.

4. Although MOVES2004 is not currently configured to estimate emissions of hydrocarbons, carbon monoxide and oxides of nitrogen, it appears that there are significant issues associated with using the basic MOVES methodology to estimate emissions of these pollutants from both the current and the future vehicle fleet. It is not clear that the modal approach on which MOVES is based will be as accurate for criteria pollutants as the approach involving a standard cycle to which correction factors are applied, as is used in MOBILE. In fact, using the MOVES methodology to predict IM147 emissions from 1994 and 1995 model year vehicles tested in the Arizona I/M program produced errors of more than 50% for some pollutants.

Given the above, it is clear that considerably more effort will be required to develop a version of MOVES that meets EPA's objectives for the model and that the current version of the MOBILE model will be in use to estimate criteria pollutant emissions for the foreseeable future.

Summarized below are some of the more interesting findings of this review. A detailed discussion of each of these topics can be found in corresponding sections of the report.

## 1.1 MOVES2004 Modal Modeling Approach

Prior to the results of this study being summarized, a brief explanation of the MOVES2004 modeling approach is warranted. At the core of MOVES2004 is the methodology developed by EPA to estimate emissions and energy consumption on a "modal" basis (i.e., on a second-by-second basis). It represents a significant departure from the methodology used in the MOBILE series of models, which were based on emissions data collected over complete test cycles (primarily the FTP) and included various correction factors to account for different speeds and operating conditions. Although the modal approach is currently limited to estimating energy consumption in MOVES2004, EPA plans to use this methodology for criteria pollutants in subsequent versions of MOVES.

In the MOVES modeling methodology, energy consumption rates (and ultimately emission rates) for different vehicle types are stored within the model in one of 17 "operating mode bins." These operating mode bins are defined on the basis of vehicle speed range (i.e., < 25 mph, 25 - 50 mph, and > 50 mph) and vehicle specific power (VSP) range (e.g., < 0 kW/tonne, 0 - 3 kW/tonne, etc.). In addition, separate operating mode bins are defined for idle operation and vehicle braking. Energy consumption rates are stored in terms of kilojoules per second, while emission rates will be stored in terms of grams per second.

Using speed-time trajectories from drive cycles built into MOVES2004 (or alternative cycles supplied by the user), the model calculates the amount of time spent in each of the 17 VSP operating mode bins. This information is linked with the energy consumption rates (or emission rates) by bin described above, and the emission rates at each second are summed over the cycle being evaluated. This approach has the advantage of being able to estimate emissions over an unlimited number of driving cycles. However, as discussed below, the data requirements are much more intensive.

## 1.2 Review of Energy and Emissions Inputs

This review focused on fuel consumption and emissions data that form the basis of the MOVES2004, as well as the various assumptions and correction factors that are applied to the data. In addition, the performance of the modal methodology fundamental to MOVES2004 was evaluated by comparing predicted fuel consumption and criteria pollutant emissions generated from the MOVES2004 database to an actual fleet of vehicles operated over a specific driving cycle.

Table 1-1 compares the VSP operating mode bin fractions that are represented by 1990 and newer model year light-duty gasoline vehicles in the MOVES2004 emissions database (i.e., EPA's Mobile Source Observation Data, MSOD) with the default travel estimates contained in the model. As observed in that table, when the MOVES2004 national default VSP bin distribution is compared to the MSOD database, significant differences are observed. This is particularly true of the high-speed VSP bins (i.e., those

| Table 1-1<br>Comparison of VSP Operating Mode Bin Fractions<br>for 1990 and Newer Light-Duty Gasoline Vehicles<br>MOVES2004 Database vs. National Default Travel Estimates<br>(Percent of Time in Each Bin) | | |
|---|---|---|
| Operating Mode Bin | Entire MSOD Database | National Default MOVES2004 Estimates |
| 0 (Braking) | 13.2% | 8.8% |
| 1 (Idle) | 6.0% | 13.9% |
| Speed < 25 mph | | |
| 11 (< 0)[a] | 6.7% | 6.0% |
| 12 (0-3) | 8.6% | 8.4% |
| 13 (3-6) | 6.1% | 4.0% |
| 14 (6-9) | 3.6% | 2.0% |
| 15 (9-12) | 3.7% | 1.7% |
| 16 (> 12) | 1.6% | 1.0% |
| Speed = 25-50 mph | | |
| 21 (< 0) | 3.2% | 4.9% |
| 22 (0-3) | 6.2% | 5.1% |
| 23 (3-6) | 11.9% | 4.2% |
| 24 (6-9) | 2.6% | 3.6% |
| 25 (9-12) | 2.1% | 2.8% |
| 26 (> 12) | 5.2% | 4.1% |
| Speed > 50 mph | | |
| 33 (< 6) | 5.1% | 7.5% |
| 35 (6-12) | 7.4% | 8.4% |
| 36 (> 12) | 6.9% | 13.5% |
| Total | 100% | 100% |

[a] Numbers in parentheses reflect the VSP range in units of kW/tonne.

over 50 mph), which constitute 29.4% of travel time but are represented by only 19.4% of the test data.

Emissions data by VSP operating mode bin for 1994 to 1997 model year vehicles were used in conjunction with the MOVES2004 national default travel time distribution by bin (from Table 1-1) to estimate the emissions contribution from each bin. The results of this analysis, which are summarized in Table 1-2, were based on the existing VSP binning structure in MOVES2004. The estimates presented in Table 1-2 indicate that although Bin 36 (speed > 50 mph and VSP > 12 kW/tonne) accounts for only 13.5% of travel time, the emissions contribution is 24.1% for HC, 50.6% for CO, 30.0% for NOx, and 27.8% for $CO_2$. This underscores the need to ensure that the high speed/high VSP bins are well-represented in any database used to generate emission factors for the next version of MOVES.

**Table 1-2**
**MOVES2004 National Default LDGV VSP Operating Mode Bin Distribution and Corresponding Emissions Contribution (1994-1997 Model Year LDGVs)**

| Operating Mode Bin | Time in Each Bin | Emissions Contribution | | | |
|---|---|---|---|---|---|
| | | HC | CO | NOx | $CO_2$ |
| 0 (Braking) | 8.8% | 3.9% | 1.4% | 1.4% | 2.9% |
| 1 (Idle) | 13.9% | 8.0% | 3.3% | 1.5% | 4.3% |
| Speed < 25 mph | | | | | |
| 11 (< 0)[a] | 6.0% | 4.8% | 1.7% | 2.5% | 2.7% |
| 12 (0-3) | 8.4% | 7.5% | 3.1% | 4.9% | 4.9% |
| 13 (3-6) | 4.0% | 5.7% | 2.4% | 4.5% | 3.6% |
| 14 (6-9) | 2.0% | 3.8% | 1.5% | 3.3% | 2.3% |
| 15 (9-12) | 1.7% | 3.2% | 1.5% | 3.3% | 2.5% |
| 16 (> 12) | 1.0% | 1.5% | 1.0% | 2.2% | 1.8% |
| Speed = 25-50 mph | | | | | |
| 21 (< 0) | 4.9% | 2.7% | 1.4% | 1.7% | 2.6% |
| 22 (0-3) | 5.1% | 3.4% | 1.5% | 2.7% | 3.5% |
| 23 (3-6) | 4.2% | 3.5% | 1.6% | 3.2% | 3.8% |
| 24 (6-9) | 3.6% | 3.5% | 2.0% | 3.9% | 4.3% |
| 25 (9-12) | 2.8% | 2.9% | 2.1% | 4.4% | 4.4% |
| 26 (> 12) | 4.1% | 8.6% | 10.9% | 14.9% | 9.8% |
| Speed > 50 mph | | | | | |
| 33 (< 6) | 7.5% | 5.9% | 6.1% | 5.1% | 6.7% |
| 35 (6-12) | 8.4% | 6.8% | 7.9% | 10.5% | 12.0% |
| 36 (> 12) | 13.5% | 24.1% | 50.6% | 30.0% | 27.8% |
| Total | 100% | 100% | 100% | 100% | 100% |

[a] Numbers in parentheses reflect the VSP range in units of kW/tonne.

The performance of the MOVES methodology in predicting emissions was evaluated by processing the underlying second-by-second MSOD emissions data and comparing those results to actual emissions data collected from vehicles that were tested in Arizona. This comparison was performed for 1994 and 1995 model-year light-duty gasoline powered vehicles because they are equipped with relatively advanced emission control systems and are well represented in the MOVES database—there are 1607 vehicles for the 1994 model year and 1584 for 1995. Emissions results from these tests were then averaged by model year and vehicle-specific-power (VSP) bins and applied to the IM147 drive trace to predict second-by-second emissions of $CO_2$, HC, CO, and NOx using the MOVES methodology. The second-by-second emissions data for these vehicles were "binned" using the current MOVES2004 binning structure as well as a more detailed, "new," binning structure proposed by EPA for criteria pollutants. In general, reasonable agreement was observed for $CO_2$ and NOx emissions, while significant differences were observed for HC and CO emissions. The results of this analysis for 1994 model year vehicles are shown in Figure 1-1 for $CO_2$ emissions and in Figure 1-2 for HC emissions.

**Figure 1-1**

**1994 MY LDGV CO2 Emissions Comparison Over the IM147 Cycle**
**MOVES2004 Database vs. Arizona IM147 Data**

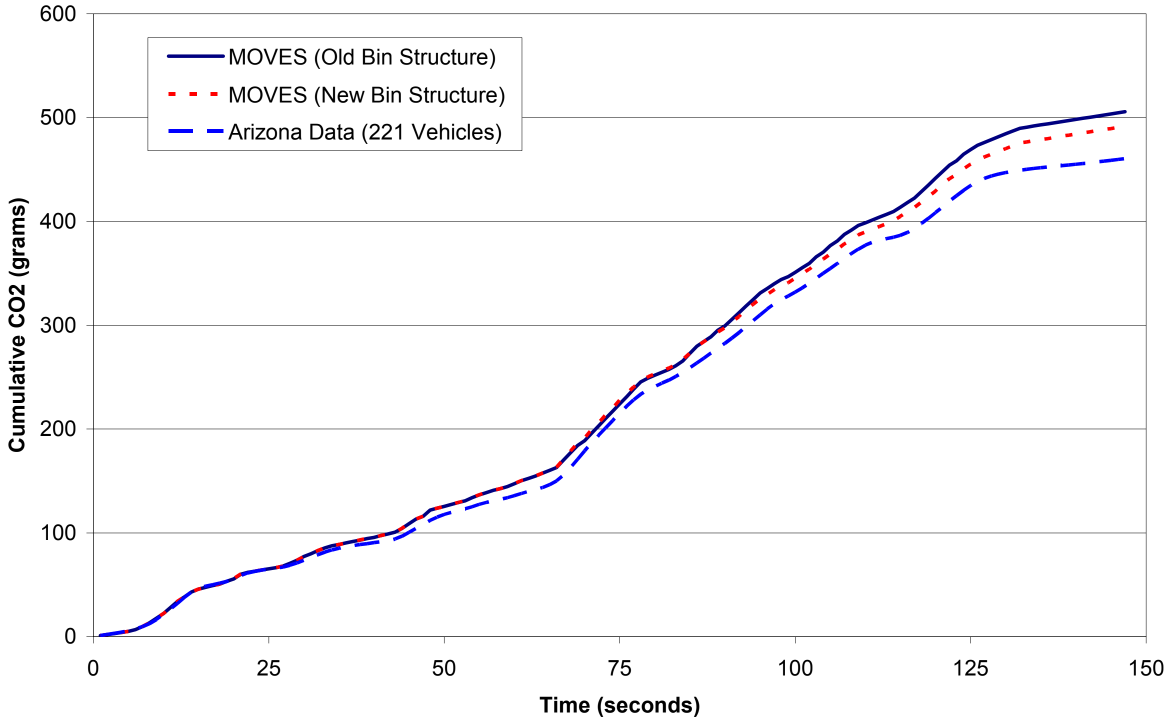
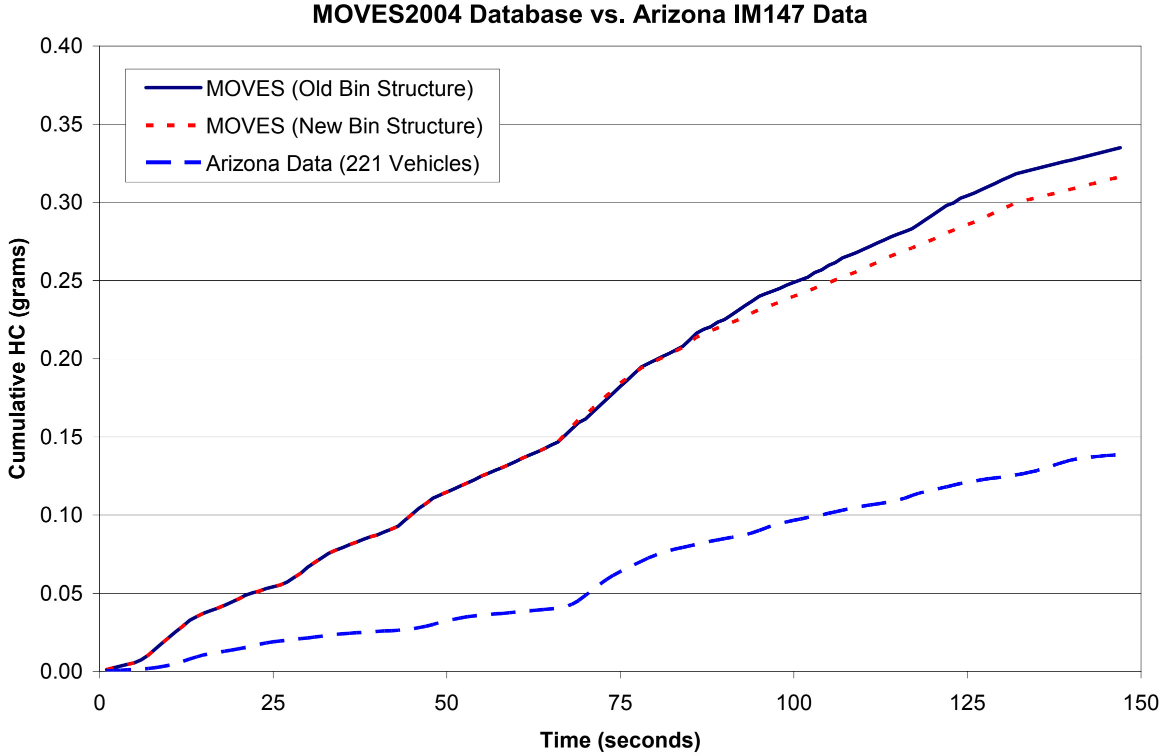



**Figure 1-2**

**1994 MY LDGV HC Emissions Comparison Over the IM147 Cycle**
**MOVES2004 Database vs. Arizona IM147 Data**



There are a number of potential reasons for the inconsistencies observed in the above figures. Most notably, the vehicle fleets used in the two analyses are different, although both were randomly selected for participation in each program. The MOVES2004 database is largely represented by vehicles tested in New York in the 1999 to 2002 timeframe. On the other hand, the Arizona IM147 sample was collected in the 1998 to 1999 timeframe. Thus, one might expect differences in the degree of emission control system deterioration between the two samples, and therefore higher emissions from the MOVES2004 estimates. However, it is very unlikely that deterioration alone is leading to the two- to three-fold difference in HC and CO emissions observed in the above figures, and these differences could be a result of inconsistencies and inaccuracies associated with the application of the MOVES2004 modal modeling approach to criteria pollutant emissions. Although very good agreement is observed in the $CO_2$ estimates, it is important not to use those favorable results to assume that this approach is necessarily valid for criteria pollutant emissions estimates.

## 1.3 Review of the PERE Model

The Physical Emission Rate Estimator, or PERE, model is used by EPA to develop default energy inputs in MOVES2004 for portions of the vehicle fleet not covered in EPA's current database and to forecast energy consumption estimates for future technology vehicles. Topics covered in our review of PERE included a general overview of the model and its inputs, evaluations of the approach used by PERE to model both existing and advanced engine technologies, analysis of PERE's ability to model criteria pollutants, and a review of earlier comments regarding PERE that were submitted to EPA.

Our review indicated that the PERE model can produce reasonable estimates of fuel consumption for conventional, gasoline-fueled vehicles. However, the reasonableness of the PERE fuel consumption estimates begins to falter for driving cycles that contain higher speeds and more aggressive accelerations than contained in the FTP and Highway Fuel Economy Test driving cycles. This is due to the greater presence of events at or near wide open throttle under which PERE's assumed linear BMEP vs. FMEP relationship is invalid.

Although the PERE model is capable of producing reasonable fuel consumption estimates for conventional technologies, the results it predicts for more advanced technologies are prone to larger errors. The fundamental problem with the way PERE handles advanced IC technologies is that it assumes they can be modeled by using a uniform improvement in engine efficiency. However, increasingly popular technologies like cylinder deactivation and variable valve lift and timing (VVLT) do not increase efficiency uniformly over the full range of engine operation. For example, cylinder deactivation improves efficiency only at light loads. At higher loads, the engine runs just like an engine that does not have a cylinder deactivation system. It should also be noted that cylinder deactivation is usually turned off at idle to prevent the engine from running too roughly. Like cylinder deactivation, variable valve lift and timing primarily improves efficiency at light loads. Unlike cylinder deactivation, VVLT does not need to be deactivated at idle.

There are also problems with the manner in which PERE is used to model hybrid vehicles. EPA assumes that hybrid vehicles will be "launched" using only their electric motor(s) to the extent that power demand is lower than the rated capacity of the electric motors. While this approach to modeling hybrids may sound superficially appealing, it is not valid. The Prius vehicle that EPA cites as an example is a case in point. As EPA notes, the Prius has a high ratio of electric motor power to combustion engine power; however, EPA's proposed approach to modeling a "full hybrid" vehicle like the Prius fails to account for the fact that the available battery power is substantially less than the available electric motor power. To use the full rated power of the electric motors, it is necessary to run the combustion engine and spin the generator. The "no charging while engine running" assumption is also a simplification that is inconsistent with the way hybrids are actually programmed. Because of these problems and the above-mentioned problems with the way engine efficiency is estimated, it is not surprising that the material EPA has presented regarding "City Fuel Economy Validation" shows poor predictions of hybrid vehicle fuel economy. EPA's conclusion that the hybrid fuel economy validation is "robust" is inconsistent with the actual data EPA has presented.

At this point, it is unclear if EPA will attempt to configure PERE to estimate criteria pollutant emissions for the next version of MOVES. If used for that purpose, we would have serious concerns about the ability of PERE to model criteria pollutant emissions for the following reasons:

- The use of aftertreatment devices to control criteria pollutant emissions to varying degrees as a function of power demand is very vehicle-specific, and automotive engineers spend a significant amount of time calibrating <u>each engine family</u> for optimum emissions performance. As a result, it is impossible to develop a single relationship relating emissions to power demand as was done in the current version of PERE for estimating fuel consumption as a function of power demand.

- Modeling of $CO_2$ emissions with a physical model such as PERE is much more straightforward than modeling criteria pollutant emissions. If an attempt is made to revise PERE to model criteria pollutants, significant uncertainty will be introduced.

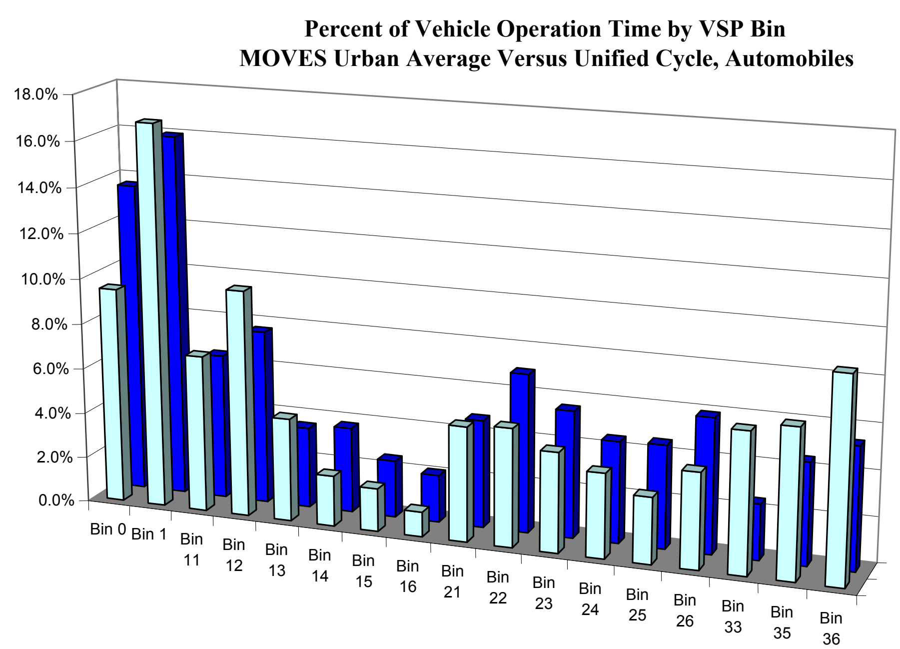
Given the above, it is doubtful that using a revised version of PERE, or a model based on PERE, to estimate criteria pollutant emissions of future technology vehicles will be any more accurate than the historical method of scaling emission rates of current technology vehicles (for which data are available) by the ratio of future-to-current emissions standards.

## 1.4 Vehicle Fleet and Activity Data

Included in this review was an evaluation of the fleet and activity data used in the MOVES model. One key element new to the MOVES model is that it includes national vehicle activity data resolved to the county level and reports total on-highway emissions and fuel economy. MOBILE6.2, in contrast, only estimates factors reported as emissions per unit of activity (e.g., grams per mile), and activity data has always been maintained separately from the MOBILE series of models. Another key element of the MOVES model is the resolution of rates by operating mode or VSP bin (fuel consumption rates and emission rates in future versions). Our review focused on the elements new to the MOVES model and in particular the methodology used to estimate the proportion of travel time by the VSP operating bins.

As part of this evaluation, we compared the default MOVES2004 urban VSP bin distribution against another self-weighted urban driving cycle (California Air Resources Board's Unified Cycle). The Unified Cycle represents urban operation in the Greater Metropolitan Los Angeles area circa 1992. The results of this comparison are shown in Figure 1-3. Overall, the VSP bin profiles shown in Figure 1-3 are similar. But differences do exist, which may in part be due to the different activity patterns in Los Angeles versus urban areas nationally.

**Figure 1-3**




| | Bin 0 | Bin 1 | Bin 11 | Bin 12 | Bin 13 | Bin 14 | Bin 15 | Bin 16 | Bin 21 | Bin 22 | Bin 23 | Bin 24 | Bin 25 | Bin 26 | Bin 33 | Bin 35 | Bin 36 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MOVES Urban Average | 9.5% | 16.9% | 6.9% | 10.0% | 4.5% | 2.2% | 1.9% | 1.1% | 5.0% | 5.2% | 4.4% | 3.7% | 2.9% | 4.2% | 6.1% | 6.5% | 8.9% |
| Unified Driving Cycle | 13.6% | 15.9% | 6.4% | 7.7% | 3.6% | 3.8% | 2.5% | 2.1% | 4.7% | 7.0% | 5.6% | 4.5% | 4.5% | 5.9% | 2.4% | 4.5% | 5.4% |

A primary concern with respect to the travel activity data in MOVES2004 is that a significant portion of travel is occurring at the high speed bins (33, 35, and 36), estimated at 29.4% of the time nationally (see Table 1-2). Also a significant portion of travel is occurring at the high VSP (bins 26 and 36 with VSP at or greater than 12 kW/tonne), estimated at 17.7%. The key issue for the accuracy of MOVES is that the supporting fuel consumption rate data (and emission rate data in later releases of MOVES) must adequately represent these bins.

## 1.5 Evaluation of MOVES2004 Fuel Consumption Estimates

This study also included a critical review of the work that EPA has performed to evaluate or "validate" the fuel consumption estimates generated by MOVES2004. In addition, an assessment was made of the accuracy of fuel consumption estimates generated by the MOVES and PERE models for three current technology vehicles that generally span the light-duty vehicle size range operating over several driving cycles representative of the range of normal vehicle operation.

As part of EPA's validation of MOVES2004, fuel economy estimates by model year from MOVES2004 were compared to published fuel economy values from the Fuel Economy Trends report for passenger cars and light-duty trucks. The MOVES2004 estimates were generated by running the model on an annual and a national basis for calendar year 2004, and specifying the output at the model year level. EPA's analysis showed that for passenger cars, the MOVES2004 fuel economy estimates are somewhat less than EPA reported for pre-1990 model years, but very nearly equal to the report values for 1990 and later model years. The MOVES2004 estimates for light-duty trucks show that fuel economy values for pre-1985 model year vehicles that are significantly less than EPA reported, but for 1985 and later model years the MOVES2004 values are in good agreement with the reported values.

EPA's overall conclusions regarding its evaluation of MOVES2004 fuel economy estimates were that "the comparisons presented in this report are encouraging, particularly the good agreement between fuel consumption estimates derived from MOVES and the top-down fuel sales data compiled by FHWA."

While the fuel consumption and fuel economy comparisons presented by the EPA tend to show reasonable agreement with other data, we would expect fuel consumption and fuel economy to be the easiest parts of the model to develop and validate, since the model is based on vehicle specific power, and these items (fuel economy and fuel consumption) are not influenced by exhaust aftertreatment systems. We would expect the validation to be much more difficult for VOC, CO, and NOx.

To serve as an independent check on the fuel consumption estimates generated by MOVES2004, Sierra and AIR performed a "bottom-up" analysis of fuel consumption predictions for three 1998 to 1999 model year vehicles run over three different driving cycles (a "hot" FTP, CARB's Unified Cycle, and a Freeway LOS A cycle). Estimates were prepared using three different fuel consumption models: MOVES2004, PERE, and VEHSIM.* Note that the key difference between MOVES2004 and PERE estimates is that MOVES is based on a 10,000-vehicle database of second-by-second test results, while PERE estimates are based on typical parameters for the three vehicles. In the case of the three 1998 to 1999 model-year vehicles modeled in this analysis, MOVES2004 contains a considerable amount of actual fuel consumption data and this evaluation represents a comparison of the data-driven performance of MOVES2004, rather than just a rehash of our evaluation of the performance of the PERE model.

The results of this analysis indicated that MOVES2004 overpredicts FTP and Unified Cycle fuel consumption for all three vehicles and underpredicts fuel consumption on the LOSA cycle for all three vehicles. The LOSA drive cycle differs from the FTP and Unified Cycles in that it has a higher average vehicle speed and does not have any stop-and-go operation. Therefore, it could be that the MOVES2004 fuel consumption estimates are being biased by a lack of data at high speeds, a lack of data from relatively steady-state operation, or overestimating fuel consumption during stop-and-go operation. In contrast, there is no apparent pattern in the fuel consumption estimates from the PERE or VEHISM models.

While the results from these three vehicles do not conclusively demonstrate a problem or flaw with the MOVES2004 model, the apparent pattern of over- and underprediction of fuel economy by MOVES2004 for these three vehicles and driving cycles, coupled with the lack of a bottom-up validation of the model, is a major concern. As noted above, it could be that the basic MOVES methodology generates biased fuel consumption estimates for different types of driving cycles, which suggests that the methodology has significant flaws. Further, if the methodology is incapable of generating accurate fuel consumption estimates, there is no reason to believe that it will be capable of generating accurate estimates of criteria pollutant emissions.

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* VEHSIM is a vehicle simulation model originally developed by General Motors Corporation and substantially modified by Sierra Research. The model calculates the instantaneous power required to propel a vehicle over any specified driving cycle based on user-supplied information regarding road surface, wind speed, roadway grade, vehicle weight, frontal area, aerodynamic drag coefficient, rolling resistance, and rotational inertia of the engine and other drivetrain components. The engine speed and load required to supply the required power is calculated from information regarding rolling radius, tire rolling resistance, axle ratio and axle efficiency, transmission gear ratios and efficiency, shift logic, torque converter characteristics and lockup schedule, and accessory power demand. Instantaneous fuel consumption is calculated by interpolation of the individual data points on an "engine map" (i.e., fuel consumption as a function of speed and load). The engine maps available for use with VEHSIM include "blended" maps for conventional engines supplied by Alliance member companies and maps for alternative engines extracted from the technical literature.

## 1.6 Methane and Nitrous Oxide Estimates

As part of this effort, the $N_2O$ and $CH_4$ emission rates used in MOVES2004 were also reviewed. This review identified a number of concerns related to the $N_2O$ emission rates:

- A number of $N_2O$ testing programs tested vehicles on both high- and low-sulfur fuels. Other testing programs used only higher sulfur fuels, like Clean Air Act baseline gasoline. Data from different programs with varying sulfur levels could have been inappropriately combined in the analysis.

- It appears that emission rates from LEV I and LEV II vehicles have been assumed to be the same. LEV II vehicles are subject to much lower NOx emission standards than LEV I vehicles; thus, it is possible their $N_2O$ emissions may be lower than those observed for LEV I vehicles. For example, MOVES2004 $N_2O$ emission factors for LEVs are much lower than Tier 1 vehicles. Further, the LEV NOx standard is 0.2 g/mi while the Tier 1 NOx standard is 0.4 g/mi. This strongly indicates that LEV II vehicles, which are subject to a NOx standard of 0.05 g/mi, should have lower $N_2O$ emissions than LEV I vehicles.

- Emissions of $N_2O$ from Tier 2 vehicles are not separately estimated. Based on the above, Tier 2 vehicles, which are subject to significantly lower NOx standards than Tier 1 vehicles, would be expected to have much lower $N_2O$ emissions. Further, MOVES2004 needs to account for the fact that the Tier 2 fleet average NOx standard applies to all vehicles under 8,500 lbs GVW, including medium-duty passenger vehicles.

- The model should be modified so that $N_2O$ emission rates vary with sulfur level, and sulfur level should be an input to the model, just like it is in the latest versions of the MOBILE series of models.

Regarding $CH_4$ emissions, there are more data from which to develop $CH_4$ emission rates than exist for developing $N_2O$ emission rates for vehicles certified to Tier 1 and less stringent standards. However, for LEVs, the EPA database includes data from only 17 vehicles. In reviewing the EPA database, we identified data from a CARB Surveillance program (CARB's 2S00C1 program) that appeared not to have been included in EPA's database. This database includes 42 passenger cars certified to either LEV (39 vehicles) or ULEV (3 vehicles) standards, as well as data from other vehicles certified to various, less stringent, emission standards. The data from the CARB program show that the $CH_4$ emission rates from the 39 LEV vehicles in the CARB database are about 34% lower than the current MOVES2004 emission rate for this class of vehicle. The data also strongly suggest that the stringency of the NMOG standard, even at very low NMOG levels, has a significant effect on $CH_4$ emissions given the substantially lower $CH_4$ emission rates of the ULEVs.

Another issue that EPA has failed to address is the impact of fuel sulfur level on $CH_4$ emissions, particularly those from vehicles certified to stringent NMOG/NMHC standards. As was recommended with respect to $N_2O$ emissions, EPA should not mix vehicles tested on high- and low-sulfur fuels, but should develop methane emission rates for use in MOVES at one sulfur level, and then develop sulfur correction factors for each technology group.

##

# 2. INTRODUCTION

For over 25 years, the U.S. EPA has used the MOBILE series of emission factor models to estimate on-road motor vehicle emissions. In very simple terms, the MOBILE model is based on emission test data from a substantial number of vehicles collected from laboratory testing of vehicles generally using the same driving cycles[*] used in vehicle and engine certification. Those data are then adjusted to account for factors known to impact emissions, such as ambient temperature, fuel composition, and vehicle speed. The MOBILE series of models has been used by the EPA as well as state and local governments to assess the emission benefits of control programs, including stringent new vehicle emissions standards, inspection and maintenance programs, and fuel property regulations. In addition, the MOBILE models have formed the basis for the development of state implementation plans (SIPs) demonstrating how compliance with National Ambient Air Quality Standards will be achieved and for demonstrating transportation plan conformity. The latest version of the MOBILE series of models, MOBILE6.2, was released by EPA in November 2003.

In response to criticism of the MOBILE series of models, as well as the need to expand the tools available for estimating emissions, EPA has spent several years developing a replacement model. This replacement model, known as "MOVES" (MOtor Vehicle Emissions Simulator), embodies significant methodology changes in the way on-road motor vehicle emissions are estimated as it uses a "modal," rather than drive-cycle based approach. The first public version of the model, MOVES2004, which was released in January 2005,[1] estimates on-road motor vehicle energy consumption as well as emissions of methane ($CH_4$) and nitrous oxide ($N_2O$), but does not generate estimates of criteria pollutant emissions (e.g., VOC, CO, NOx, PM, and SOx). At the time MOVES2004 was released, EPA requested that public comments on the model be submitted by July 15, 2005.

Although MOVES2004 does not generate estimates of criteria pollutants, EPA has made it clear that subsequent versions of MOVES will use the same basic methodologies embodied in MOVES2004 to estimate criteria pollutant emissions from on-road motor vehicles. In addition, it is clear that EPA intends for MOVES to be used in assessing the need for and the emission benefits of a wide range of on-road motor vehicle emission

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[*] The primary certification driving cycle is commonly referred as the FTP, a term that is used in this report. The FTP involves collection of emissions in sampling bags over three driving segments. These segments and the emissions occurring during them are referred to as Bag 1, Bag 2, and Bag 3. Bag 1 generally represents cold start operation, Bag 2 generally represents hot stabilized operation, and Bag 3 generally represents hot start operation.

control measures, including changes in fuel type (e.g., substitution of hydrogen for gasoline) and vehicle type (e.g., substitution of hybrid or fuel cell vehicles for conventional vehicles) and in SIP development.

Clearly, substituting a MOVES model developed using fundamentally new methodologies for the existing MOBILE6.2 model raises issues with all aspects of the estimation of emissions from on-road motor vehicles. As a result, a careful review of the MOVES2004 model is warranted to understand how the model is structured, what data the model is based on, and how the model operates. Further, this review needs to focus not only on the estimates of energy consumption and $CH_4$ and $N_2O$ emissions currently available from MOVES2004, but also on the implications that the model structure, data, and operation have for the estimation of criteria pollutant emissions in future MOVES versions.

Given the implications that MOVES presents for the automobile industry and EPA's request for public comment on MOVES2004, the Alliance of Automobile Manufacturers commissioned Sierra Research, Inc. and AIR Improvement Resource to conduct a review of the MOVES2004 model as it relates to gasoline- and Diesel-fueled motor vehicles with gross vehicle weight ratings (GVWR) of 10,000 lbs or less (excluding motorcycles), as well as gasoline vehicles with GVWR ratings above 10,000 lbs. This report presents the results of that review, following an overview of modal emissions methodology that forms the heart of MOVES2004.

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# 3. OVERVIEW OF MOVES2004

As noted previously, in contrast to MOBILE6.2, MOVES2004 uses a modal approach to estimate energy consumption from the on-road motor vehicle fleet during running operation. In addition to estimating energy consumption during vehicle operation, MOVES2004 also estimates energy consumption during vehicle starts based on bagged FTP data (an offset is calculated from the difference of Bag 1 and Bag 3) and predicts energy consumption during extended idle periods (e.g., "hoteling" practices of long-haul trucks). MOVES2004 can be configured to estimate the fuel consumption of a single vehicle operating over a specified driving cycle, fuel consumption for the fleet of vehicles operating in a given city, or even the fuel consumption of all vehicles operating in the U.S. In addition, as noted above MOVES2004 provides similar estimates emissions of $CH_4$ and $N_2O$.

In this section, we present an overview of how MOVES2004 estimates fuel consumption and emissions of $CH_4$ and $N_2O$ based on our understanding of the model and associated documentation. This provides a point of reference for the results of our review of the different facets of the model, as well as the underlying data and methodologies discussed in subsequent sections.

## 3.1 Estimation of Fuel Consumption Using A Single Driving Cycle

The modal methodology developed by EPA represents a significant departure from the methodology used in the MOBILE series of models, which were based on emissions data collected over complete test cycles (primarily the FTP) and included various correction factors to account for different speeds and operating conditions. The modal methodology used in MOVES2004 to estimate energy consumption during running vehicle operation can be simplified into the following steps.

1. Segregation of the vehicle fleet into specific "**Source Bins**," which, for total energy consumption estimates, include the following:

    - Fuel type (gasoline, Diesel, etc.)
    - Engine technology (conventional internal combustion, advanced internal combustion, moderate hybrid, full hybrid, etc.)
    - Model year group (pre-1980, 1981-1985, 1986-1990, etc.)
    - Loaded weight (≤ 2000 lbs., 2001-2500, 2501-3000, etc.)
    - Engine size (< 2.0 liters, 2.1-2.5, 2.6-3.0, etc.)

- Vehicle class (passenger cars, passenger light-duty trucks, single unit heavy-duty trucks, combination heavy-duty trucks, buses, etc.)

2. For each combination of the above source bins (e.g., gasoline, conventional IC, 1986-1990 model year, 2501-3000 lbs., 2.0 - 2.5 liter), energy usage rates (in units of kilojoules per second, kJ/s) are calculated for 17 different "**Operating Mode Bins**," which are defined on the basis of a vehicle speed range and vehicle specific power (VSP) range as well as for braking and idle operation.

   MOVES2004 defines VSP as follows:

   $$VSP = (A*Speed + B*Speed^2 + C*Speed^3 + Mass*Speed*Accel)/Mass$$

   Where VSP has units of kW/metric ton or tonne, and

   Speed = meters per second (m/s)
   A = rolling resistance (in units of kW/(m/s))
   B = friction (in units of $kW/(m/s)^2$)
   C = aerodynamic drag (in units of $kW/(m/s)^3$)
   Mass = in metric tons. A metric ton or "tonne" is 1000 kg.
   Accel = meters per second per second ($m/s^2$)

   The matrix defining the 17 operating mode bins in MOVES2004 is presented in Table 3-1, where the bins are identified using the MOVES nomenclature which does not number them consecutively from 1 to 17.

**Table 3-1**
**Operating Mode Bins in MOVES 2004**

| **Braking** -- Bin 0 | | | |
|---|---|---|---|
| **Idle** -- Bin 1 | | | |
| VSP Range (kW/tonne) | Speed Range | | |
| | 0 - 25 mph | 25 - 50 mph | > 50 mph |
| < 0 | Bin 11 | Bin 21 | |
| 0 – 3 | Bin 12 | Bin 22 | |
| 3 – 6 | Bin 13 | Bin 23 | |
| 6 – 9 | Bin 14 | Bin 24 | |
| 9 – 12 | Bin 15 | Bin 25 | |
| >= 12 | Bin 16 | Bin 26 | Bin 36 |
| 6 – 12 | | | Bin 35 |
| < 6 | | | Bin 33 |

The second-by-second energy consumption rates in MOVES2004 are based on EPA's analysis of data collected by EPA, the California Air Resources Board, UC Riverside, West Virginia University, the State of New York, and other agencies and research institutions. Note that in cases where data were not available to fill all of the above operating mode bins for each of the source bin categories, estimates were developed by (1) using the Physical Emission Rate Estimator (PERE) to generate data to fill data gaps directly, or (2) interpolating/copying of data from neighboring bins that are populated with data.

3. Energy consumption for each driving cycle for a specific source bin (MOVES defines 40 driving cycles of which 14 are used for light-duty vehicle modeling) is calculated by the following procedure.

    a. The amount of time spent in each of the 17 operating mode bins is determined by calculating the VSP distribution for the driving cycle according to the time trace of the cycle and the VSP equation coefficients of the Source Bin (coefficients A, B and C and vehicle mass as defined in the equation shown above).

    b. Once the amount of time spent in each VSP-speed bin is determined, that distribution is applied to the energy consumption rates (or emission rates in future versions of MOVES) that are stored in the model as a function of source bin. This results in an estimate of kJ per source hours of operation (SHO).

    c. SHO for a driving cycle is estimated by the distance traveled divided by the average speed.

    d. Multiplying the results of steps b and c results in the MOVES2004 estimate of total energy usage for a single driving cycle.

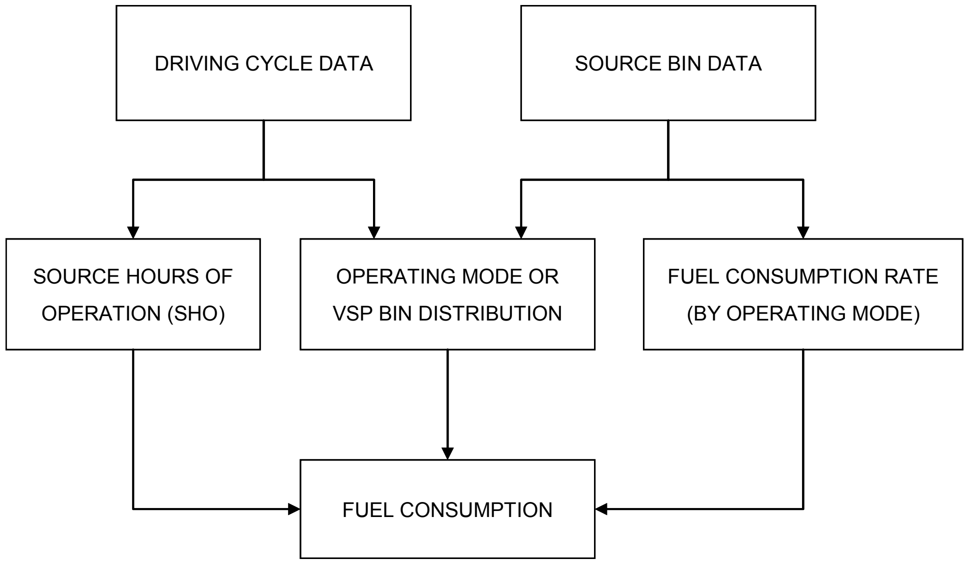
A simplified schematic flow chart showing how MOVES2004 estimates fuel consumption for vehicles operating over a single driving cycle is shown in Figure 3-1.

## 3.2 Estimation of Fuel Consumption for a Fleet of Vehicles in a Large Area

The approach discussed in Section 3.1 is extrapolated by MOVES to larger geographic areas by defining the Source Bin distribution (i.e., the proportion of specific source types present in the overall fleet) and by defining the speed distribution by roadway type and the proportion of travel by roadway type.

The Source Bin distribution describes the characteristics of the fleet population as a distribution among the Source Bins. The Source Bins classify a vehicle by parameters

**Figure 3-1**
**MOVES2004 Estimation of Fuel Consumption over a Single Driving Cycle**




relevant for emissions and energy calculations: fuel and engine technology, average vehicle weight, engine displacement, model year group, and regulatory class. MOVES estimates the Source Bin distribution using a number of input parameters including calendar year, technology implementation rates, survival rates, sales assumptions and mileage accumulation rates.

The Source Bin distribution is estimated by roadway type as the proportion of vehicle types can differ by roadway (e.g., rural Interstates can have a higher proportion of heavy-duty combination trucks). MOVES defines 12 roadway types, based on those defined by the federal Highway Performance Monitoring System (HPMS), consisting of 6 urban and 6 rural roadway types.

For a larger geographic area, MOVES determines the overall fuel consumption from speed distribution data by roadway, total travel by roadway, and VSP distributions by driving cycle in the following manner.

a. Total SHO of each roadway and speed bin are estimated by the VMT apportioned to the roadway/speed bin divided by the average speed. MOVES tracks 16 speed bins. 14 bins are defined by 5 mph ranges starting with 2.5 mph to 72.5 mph, and two additional bins account for travel below 2.5 mph and travel above 72.5 mph.

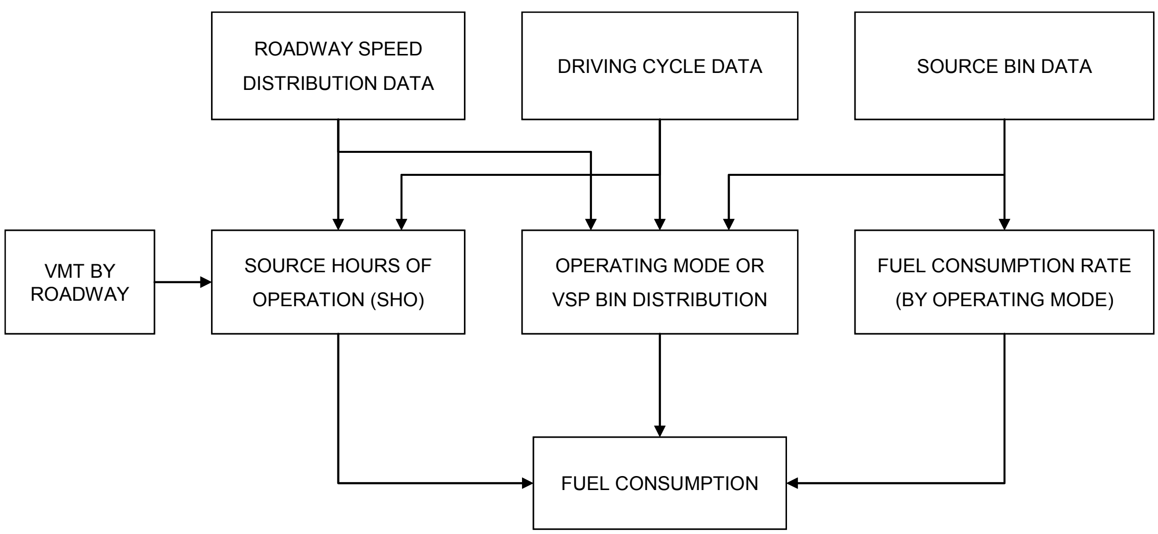
b. The VSP bin distribution of each roadway/speed bin is then determined from the VSP bin distributions estimated for the 40 driving cycles (14 of these used for light-duty modeling) by examining the driving cycles that bracket the roadway/speed bin. For example, light-duty vehicle freeway operation at 55 mph would use the light-duty Freeway LOS D cycle (average speed of 52.87 mph) and light-duty Freeway LOS AC cycle (average speed of 59.66 mph).* The VSP bin distributions for the two bracketing cycles are averaged together, weighted by the proximity of the roadway average speed to the driving cycle average speeds. Thus, the VSP distribution of any roadway average speed is determined from the two cycles that most closely bracket the roadway average speed.

c. Once the amount of time spent in each VSP bin is determined, that distribution is applied to the energy consumption rates (or emission rates in future versions of MOVES) that are stored in the model as a function of Source Bin. This results in an estimate of kJ per SHO.

d. Total fuel consumption is then estimated by the multiplication of steps a and c and summation across roadway/speed bins.

A simplified schematic flow chart showing how MOVES2004 estimates fuel consumption for a fleet of vehicles operating in a large area is shown in Figure 3-2.

**Figure 3-2**
**MOVES2004 Estimation of Fuel Consumption for a Vehicle Fleet**




## 3.3 Estimation of $CH_4$ and $N_2O$ Emissions

In contrast to the methodology described above for estimating fuel consumption (which EPA has indicated will also be used for the estimation of criteria pollutant emissions),

* These cycles, which were developed for EPA by Sierra Research, represent freeway operation in urban areas under different levels of traffic congestion.

MOVES2004 estimates emissions of $CH_4$ and $N_2O$ in essentially the same way in which the MOBILE series of models estimates emissions.

MOVES2004 contains emission rate estimates for both of these compounds based on emissions data from different types of vehicles. Emissions are estimated for starts in g/start, and the running emissions are estimated first in g/mi, and then converted to g/hour using the time of the FTP driving cycle over which the data were collected. These factors are then simply multiplied by the assumed start activity and SHO by vehicle class. In MOVES2004, there are no temperature, speed, or fuel correction factors that are used to adjust the $CH_4$ and $N_2O$ emission rate estimates for conditions that differ from those that existed during data collection. However, EPA has stated that it plans to add such correction factors in later versions of MOVES.

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# 4. REVIEW OF MOVES2004 ENERGY CONSUMPTION AND EMISSIONS INPUT DATA

As discussed in the previous section, MOVES2004 is designed to use actual data from a large number of vehicle tests to generate estimates of fleet fuel consumption and ultimately criteria pollutant emissions. In this section, we present the results of a critical review of the fuel consumption and emissions data that form the basis of the model, as well as the various assumptions and correction factors that are applied to the data. In addition, we present results of an evaluation of the performance of the modal methodology fundamental to MOVES2004 and its successors in predicting fuel consumption and criteria pollutant emissions from an actual fleet of vehicles operated over a specific driving cycle.

## 4.1 Overview of MOVES2004 Inputs

The development of the energy and emissions inputs for MOVES2004 is described in the March 2005 draft report, "MOVES2004 Energy and Emission Inputs."[2] At the core of the MOVES2004 model are the second-by-second fuel consumption data developed by EPA from the Mobile Source Observation Database (MSOD). This database includes second-by-second energy consumption rates based on the analysis of modal data collected by EPA, CARB, UC Riverside, West Virginia University, the State of New York, and other agencies and research institutions. MOVES2004 uses this second-by-second data as described in Section 3 to estimate fuel consumption. However, the model also incorporates a separate algorithm for estimating fuel consumption during vehicle start events as well as correction factors that account for the impacts of air conditioner usage and ambient temperature.

The definition of start energy consumption for MOVES follows a similar approach to that taken by the MOBILE6 model. With this approach, "start" energy is defined as the energy consumed at startup over and above the energy that would be consumed had the vehicle followed the same trajectory during running (warmed-up) operation. Start energy rates are therefore the incremental amount of energy consumed at start-up, and start rates are developed in the units of kJ per start. Incremental start energy in MOVES is modeled as the difference between Bag 1 and Bag 3 of the FTP.

In a stepwise regression analysis, EPA determined that engine displacement and model year groups were the key variables for grouping light-duty gasoline vehicle start emissions. Start energy rates, in terms of kJ per start, were then calculated for each combination of engine displacement and model year group by averaging the start (Bag 1 minus Bag 3) results for all FTP tests from vehicles falling in those bins. EPA's Mobile Source Observation Database (MSOD) as of April 2003 served as the data source for MOVES start energy rates, producing a database of 18,676 FTPs performed on 10,422 vehicles.*

Separate start energy consumption rates were also estimated for other source types (light-duty Diesel, heavy-duty gasoline, heavy-duty Diesel, and motorcycles). These were developed largely on assumptions, given a lack of sufficient test data. For example, heavy-duty gasoline start energy consumption rates are based on those estimated for pre-1981 light-duty gasoline vehicles.

Temperature corrections in MOVES are applied only to start energy consumption rates. EPA found that stabilized running energy consumption did not exhibit a temperature dependency, and therefore the model does not contain any temperature adjustments to the modal fuel consumption rates used to estimate running energy consumption.

The same MSOD used to develop the light-duty gasoline start energy consumption rates was also used to develop the temperature corrections. A total of 2,818 FTP tests on 580 light-duty gasoline vehicles fell within the criteria of containing at least one test in the 68 and 86 degrees Fahrenheit range used to develop the start energy consumption rates and at least one test outside of this range. These tests were used to develop the following quadratic adjustment equation (assumed to equal 1.0 at 75 degrees Fahrenheit), where *T* is the ambient modeling temperature:

$$\text{Gasoline Temperature Factor} = 0.000219 * (T - 75)^2 - 0.01971 * (T - 75) + 1.0$$

This single equation is used for all gasoline source types and model years.

## 4.2 Critical Review of MOVES2004 Energy and Emissions Inputs

In this section we present the results of our critical review of the energy and emissions inputs to MOVES2004, as well as the implications of those findings relative to using the MOVES methodology for estimating criteria pollutant emissions.

Distribution of MSOD Data by VSP Bin – An analysis of vehicle tests in the MSOD database upon which MOVES2004 is based was performed to compare their composite VSP bin distribution to the default light-duty vehicle VSP distribution loaded into the model by EPA. As with EPA's default MOVES2004 VSP distribution, the distribution calculated from the detailed MSOD data was time-based, i.e., it represented the fraction or percentages of time spent in each VSP bin. The MSOD-derived VSP distribution was calculated as follows.

* FTP tests were restricted to those measured at temperatures between 68 and 86 degrees Fahrenheit; the results are assumed to reflect a nominal temperature of 75 degrees Fahrenheit.

First, a file provided by EPA (MOVES_12142004.txt) that contained detailed second-by-second emission test results for every vehicle in the MSOD database was analyzed to cull out counts of individual tests by test procedure (i.e., driving cycle) for 1990 and newer (Tier 0 and later) light-duty gasoline vehicles (LDGVs). A total of 15,610 unique vehicle tests encompassing 36 different test procedures with model years between 1990 and 2001 were extracted from this file. This vehicle test tabulation is shown in Table 4-1.

**Table 4-1**
**MSOD 1990 and Newer Model Year LDGV Tests**

| Test Procedure | # of Tests | % of Tests |
|---|---|---|
| 3IM240 | 32 | 0.2% |
| ART-AB | 103 | 0.7% |
| ART-CD | 103 | 0.7% |
| ART-EF | 118 | 0.8% |
| F505 | 49 | 0.3% |
| FTP | 587 | 3.8% |
| FWY | 5 | 0.0% |
| FWY-AC | 123 | 0.8% |
| FWY-D | 103 | 0.7% |
| FWY-E | 102 | 0.7% |
| FWY-F | 118 | 0.8% |
| FWY-G | 103 | 0.7% |
| FWY-HI | 126 | 0.8% |
| IM240 | 12,757 | 81.7% |
| LA4 | 50 | 0.3% |
| LA92 | 134 | 0.9% |
| LOCAL | 103 | 0.7% |
| MEC5 | 13 | 0.1% |
| MEC6 | 37 | 0.2% |
| MEC7 | 75 | 0.5% |
| NONFRW | 102 | 0.7% |
| NYCC | 131 | 0.8% |
| RAMP | 103 | 0.7% |
| SC03 | 6 | 0.0% |
| SMEC6 | 1 | 0.0% |
| SMEC7 | 4 | 0.0% |
| ST01 | 145 | 0.9% |
| UCC15 | 12 | 0.1% |
| UCC20 | 12 | 0.1% |
| UCC25 | 12 | 0.1% |
| UCC30 | 12 | 0.1% |
| UCC35 | 12 | 0.1% |
| UCC40 | 11 | 0.1% |
| UCC45 | 12 | 0.1% |
| UCC50 | 11 | 0.1% |
| US06 | 183 | 1.2% |
| Totals | 15,610 | 100.0% |

Several points can be made with respect to the distribution of vehicle tests summarized in Table 4-1:

- The vast majority (over 80%) of emissions tests included in the MOVES2004 database were conducted with the IM240 procedure, and most of those tests were collected in the New York State Instrumentation/Protocol Assessment Study. The vehicles and fuels tested in this study are not representative of the overall US vehicle fleet and fuel mix and may create flaws in the output when modeling in-use driving patterns not represented by the IM240 cycle. Issues of data quality of this IM-based test program (compared to more controlled laboratory testing such as the FTP) are compounded by the heavy proportion of the data that the NYIPA represents in MOVES2004.

- The second-highest test total is for the FTP, which constitutes almost 4% of the total tests in the MSOD database.

- High-speed/high-load tests (e.g., the higher speed freeway cycles and the US06) make up a small fraction of the overall test results contained in the MSOD database. As a result, there is concern that those operating conditions may be under-represented by the test data.

A broader concern with respect to the data used in MOVES is that the data were limited to tests in which emissions were measured on a second-by-second basis. This essentially ignores a vast wealth of FTP data that have been collected over the last three decades.

Second-by-second speed versus time traces for each of these test procedures also supplied from EPA's MSOD database were then analyzed with a short SAS program to calculate the VSP at each second of the trace and distribute the calculated VSP into the VSP bins as defined by EPA. (In this program average LDGV mass and road load coefficients were used.) The resulting VSP bin distributions for each of the 36 test procedures were then weighted with the MSOD test populations shown earlier in Table 4-1 and re-normalized to produce a composite LDGV MSOD-based VSP bin frequency distribution. The results of that analysis are summarized in Table 4-2.

Three sets of VSP operating mode bin distributions are shown in Table 4-2: (1) the distribution based on the MSOD database as described above, (2) the distribution for the IM240 test procedure, and (3) a distribution based on the default travel activity data contained in MOVES2004. (Note that the development of the national default MOVES2004 VSP bin distribution is described in Section 6 of this report.) Not surprisingly, the distribution calculated from the MSOD data is very similar to the IM240 test procedure. However, when the MOVES2004 national default VSP bin distribution is compared to the MSOD database, significant differences are observed. This is particularly true of the high-speed VSP bins (i.e., those over 50 mph), which constitute 29.4% of travel time but are only represented by 19.4% of the test data. Because these bins are also likely to account for a disproportionate fraction of emissions and fuel

| Table 4-2<br>LDGV Operating Mode Bin Distributions<br>Comparison of MSOD Database to National Default MOVES2004 Estimates<br>(Percent of Time in Each Bin) | | | |
|---|---|---|---|
| Operating Mode Bin | IM240 Test Procedure | Entire MSOD Database | National Default MOVES2004 Estimates |
| 0 (Braking) | 13.8% | 13.2% | 8.8% |
| 1 (Idle) | 4.6% | 6.0% | 13.9% |
| Speed < 25 mph | | | |
| 11 (< 0)[a] | 6.7% | 6.7% | 6.0% |
| 12 (0-3) | 8.4% | 8.6% | 8.4% |
| 13 (3-6) | 6.3% | 6.1% | 4.0% |
| 14 (6-9) | 3.8% | 3.6% | 2.0% |
| 15 (9-12) | 4.2% | 3.7% | 1.7% |
| 16 (> 12) | 1.7% | 1.6% | 1.0% |
| Speed = 25-50 mph | | | |
| 21 (< 0) | 2.9% | 3.2% | 4.9% |
| 22 (0-3) | 6.3% | 6.2% | 5.1% |
| 23 (3-6) | 13.4% | 11.9% | 4.2% |
| 24 (6-9) | 2.5% | 2.6% | 3.6% |
| 25 (9-12) | 2.1% | 2.1% | 2.8% |
| 26 (> 12) | 5.4% | 5.2% | 4.1% |
| Speed > 50 mph | | | |
| 33 (< 6) | 4.2% | 5.1% | 7.5% |
| 35 (6-12) | 7.5% | 7.4% | 8.4% |
| 36 (> 12) | 6.3% | 6.9% | 13.5% |
| Total | 100% | 100% | 100% |

[a] Numbers in parentheses reflect the VSP range in units of kW/tonne.

consumption, it is important to accurately reflect in-use emissions in these operating mode bins. This issue is explored further later in this section of the report.

Start Emissions – As noted above, similar to MOBILE6, start emissions in MOVES2004 are calculated as an offset. Our review found that EPA's analysis showed that for fuel consumption, [Bag 1 - hot running 505] was nearly identical to [Bag 1 - Bag 3] and that EPA simply used [Bag 1 - Bag 3] as the cold start offset for MOVES2004. We believe that this approach is reasonable for modeling the incremental energy consumption for a cold start as defined in the FTP, i.e., after a 12- to 36-hour soak. However, for soak periods between 10 minutes (i.e., the Bag 3 soak period) and 12 hours, correction factors should be developed that account for differences in fuel consumption as a function of soak time. This will be particularly important as EPA moves forward with subsequent versions of the model that incorporate criteria pollutant emissions estimates. For criteria pollutants, it is likely EPA will rely on the same methodology used by MOBILE6 to estimate the emissions impacts of vehicle starts following soak times of less than 12 hours. That approach applies a multiplicative correction factor (ranging from zero at zero soak time to 1.0 at 12 hours) to the 12-hour cold-start emission rate. As part of the development of a similar “warm-start algorithm” for the next iteration of MOVES, EPA should also include $CO_2$ emissions and energy usage.

Our review also found that EPA regression analysis of fuel consumption data showed that the start offset for fuel consumption was a function of model year and engine displacement. EPA then modeled start emissions as a function of these parameters, which we also believe is reasonable. Fuel consumption during starting for hybrid vehicles is modeled in MOVES in the same manner.

Air Conditioning – The approach used in MOVES2004 to account for the impacts of air conditioning use on fuel consumption is also similar to that incorporated into MOBILE6. Full-usage correction factors are contained within the model. These are then scaled to account for compressor-on time based on temperature/humidity (“heat index”). The air conditioning factors are applied as multipliers and are a function of operating mode bin. For example, the fuel usage multiplier for bin 36 (>50 mph, >= 12 VSP) is 1.20 while the factor for bin 1 (idle) is 1.36. However, it is important to note that these factors apply only to fuel consumption and that additional factors will have to be specifically developed for criteria pollutants.

In general, we believe that it is reasonable to incorporate this previously established methodology into MOVES2004. However, one issue is that the same set of factors is applied to all vehicle types. This does not appear to be reasonable, as one would expect that correction factors for trucks would differ from those that apply to passenger cars, given that the trucks generally have smaller cab volumes and higher horsepower engines and therefore the air conditioner would be expected to draw a lower fraction of available power from the engine. EPA recognized this in MOBILE6, where different factors were developed for cars and trucks and we believe that the agency should develop different factors for use in MOVES2004.

Temperature Corrections – MOVES2004 incorporates temperature correction only for fuel consumption during starting. Our review indicates that the analysis performed by EPA did not show much impact of temperature on $CO_2$ during running operation and we believe that the general methodology used by EPA to develop the temperature correction factors for fuel consumption during starting is reasonable. With respect to criteria pollutants, however, it is not at all clear that only correcting starting emissions for temperature effects will be appropriate. Thus, before going forward with a criteria pollutant version of MOVES, the impacts of temperature on running vehicle operation must be carefully reviewed.

## 4.3 Evaluation of Criteria Pollutant Emissions Using the MOVES2004 Database and Methodology

As noted above, we are concerned that the database upon which MOVES2004 is based may not be sufficient to generate reliable estimates of in-use vehicle criteria pollutant emission rates. In particular, the high-speed VSP bins, which are thought to contribute a significant fraction of emissions, appear to be under-represented in the existing MSOD database. This section of the report explores this issue further.

Using the MOVES2004 database, average HC, CO, NOx, and $CO_2$ emissions (in grams per second) were generated for 1990 and newer LDGVs for each of the 17 VSP operating mode bins defined in MOVES2004. In addition, the data were also segregated into a "new" bin structure that we understand EPA is considering for later versions of MOVES. In this new bin structure, VSP bins 26 and 36 are further disaggregated into bins 26, 27, 28, 29 and 36, 37, 38, 39, respectively, as shown in Table 4-3.

**Table 4-3**
**New Binning Structure Proposed for Next Criteria Pollutant Version of MOVES**

| **Braking** -- Bin 0 | | | |
|---|---|---|---|
| **Idle** -- Bin 1 | | | |
| VSP Range (kW/tonne) | Speed Range | | |
| | 0 - 25 mph | 25 - 50 mph | > 50 mph |
| < 0 | Bin 11 | Bin 21 | |
| 0 - 3 | Bin 12 | Bin 22 | |
| 3 - 6 | Bin 13 | Bin 23 | |
| 6 - 9 | Bin 14 | Bin 24 | |
| 9 - 12 | Bin 15 | Bin 25 | |
| ≥ 12 | Bin 16 | | |
| 12 - 18 | | Bin 26 | Bin 36 |
| 18 - 24 | | Bin 27 | Bin 37 |
| 24 - 30 | | Bin 28 | Bin 38 |
| ≥ 30 | | Bin 29 | Bin 39 |
| 6 - 12 | | | Bin 35 |
| < 6 | | | Bin 33 |

Average results for 1994 to 1997 model year LDGVs (during which the federal Tier 1 standards were fully phased-in) were calculated for each bin. The results of that analysis are summarized in Figures 4-1 to 4-4 for HC, CO, NOx, and $CO_2$ emissions, respectively, following the format developed by EPA for presentation of mean energy rates at the March 2005 MOVES workshop.

**Figure 4-1**

**Mean HC Emission Rate by Operating Mode Bin**
**1994 to 1997 Model Year LDGVs from the MOVES2004 Database**

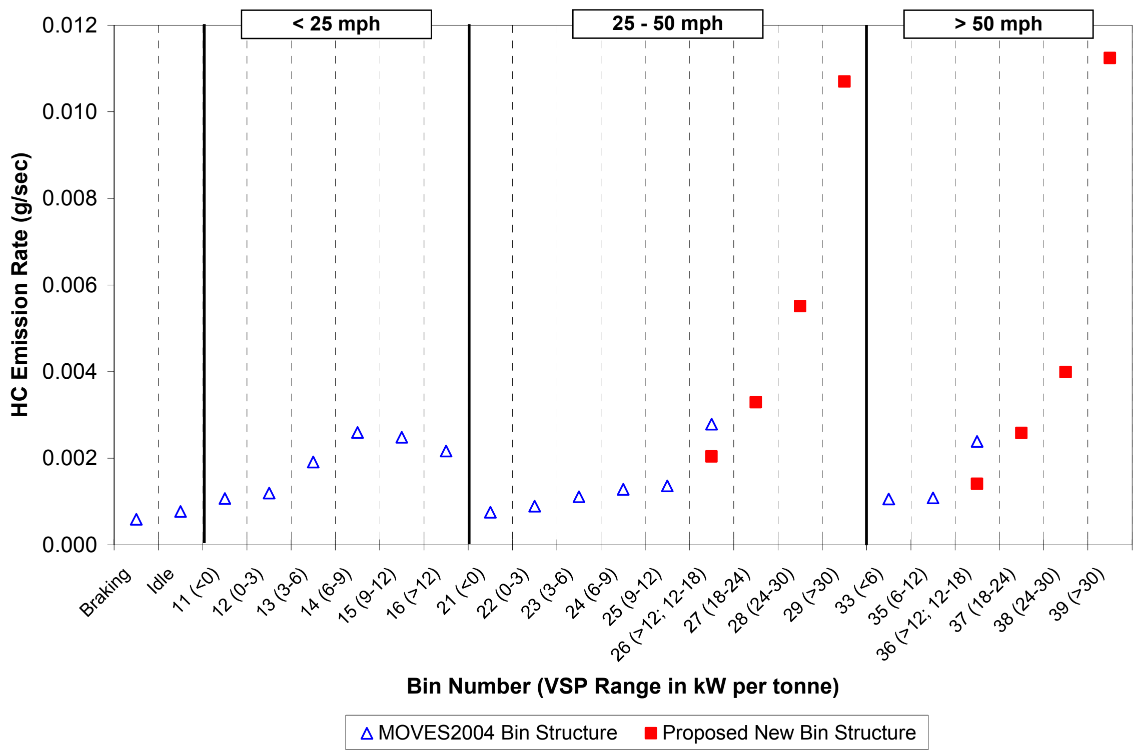
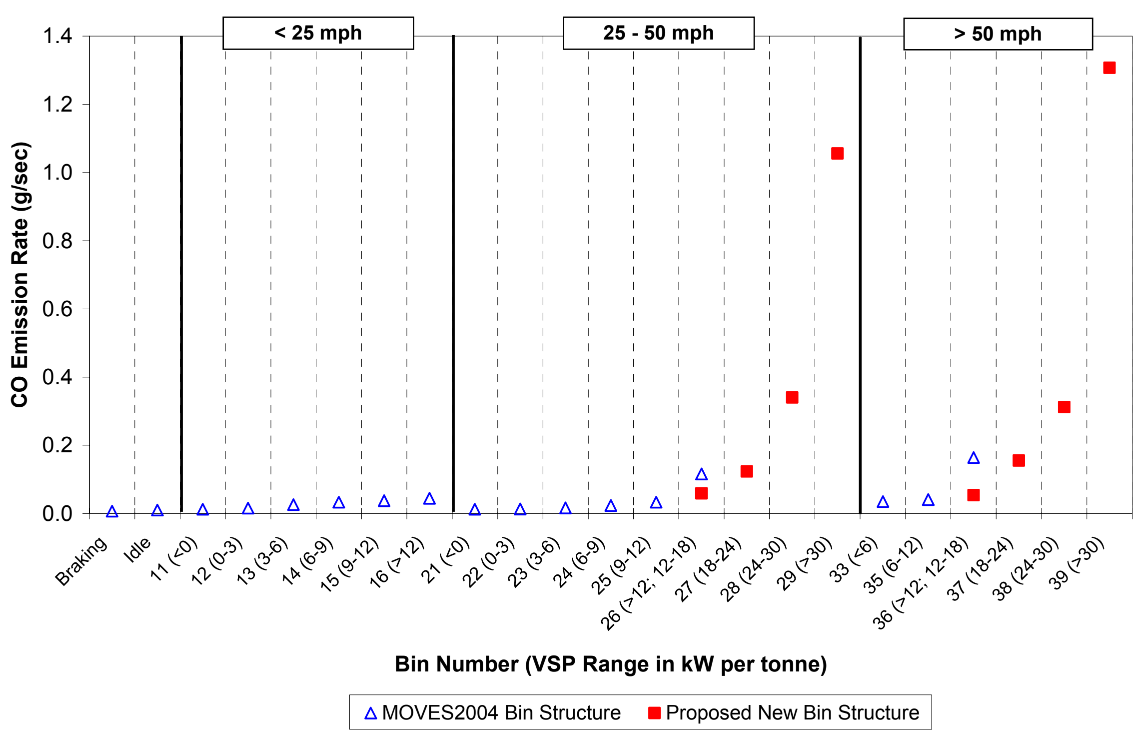


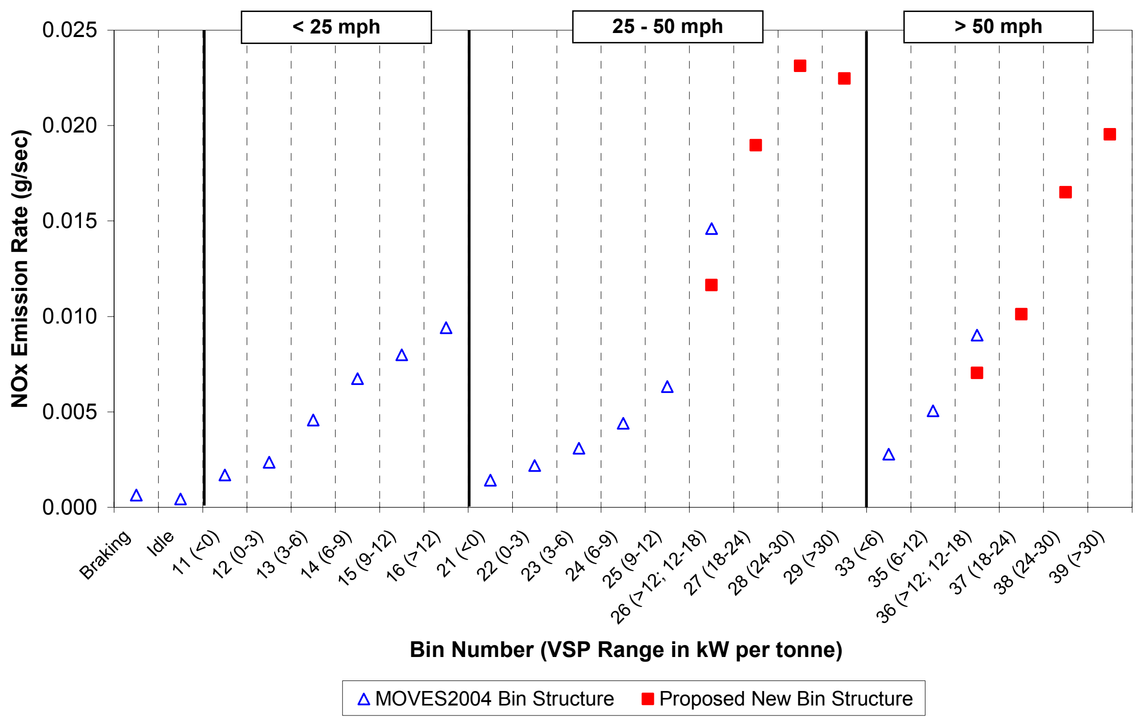

**Figure 4-2**

**Mean CO Emission Rate by Operating Mode Bin**
**1994 to 1997 Model Year LDGVs from the MOVES2004 Database**



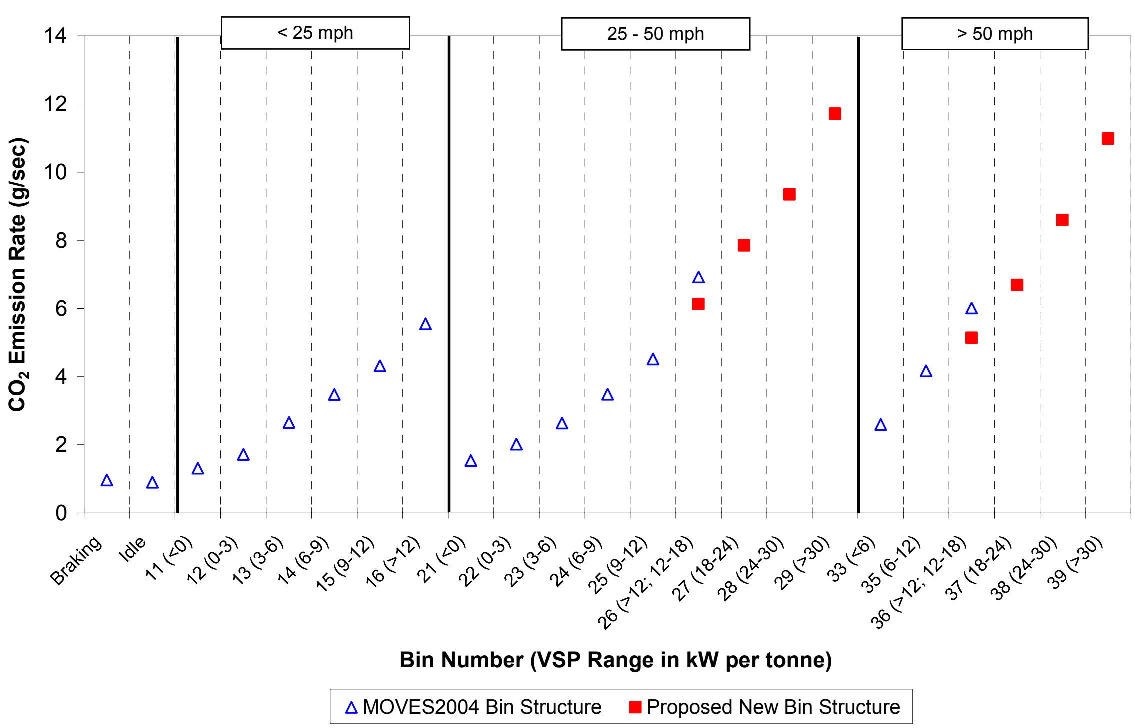
## Figure 4-3

**Mean NOx Emission Rate by Operating Mode Bin**
**1994 to 1997 Model Year LDGVs from the MOVES2004 Database**




## Figure 4-4

**Mean $CO_2$ Emission Rate by Operating Mode Bin**
**1994 to 1997 Model Year LDGVs from the MOVES2004 Database**



Several points are worth noting with respect to the results presented in Figures 4-1 to 4-4:

- As expected, emission rates increase in the higher speed/higher VSP bins. This is particularly apparent for HC and CO emissions shown in Figures 4-1 and 4-2, respectively. In fact, the range of emission rates across the VSP operating mode bins is greater than an order of magnitude for these pollutants.

- Use of the new binning structure results in continuing increases in g/sec emission rates as the VSP increases within a speed range. Again, this increase is most notable with HC and CO emissions.

- The shape of the NOx and $CO_2$ emission "curves" are very similar as shown in Figures 4-3 and 4-4, respectively. This is not unexpected, as both compounds are related to power demand on the engine. It is interesting to note, however, the slight drop in NOx emissions between Bin 28 and Bin 29 (in the new binning structure). This is likely a result of enrichment, thus suppressing NOx formation.

The emissions data by VSP operating mode bin shown in Figures 4-1 to 4-4 were used in conjunction with the MOVES2004 national default travel time distribution by bin (from Table 4-2) to estimate the emissions contribution from each bin. The results of this analysis, which are summarized in Table 4-4, were based on the existing VSP binning structure in MOVES2004. The estimates presented in Table 4-4 indicate that although Bin 36 (speed > 50 mph and VSP > 12 kW/tonne) accounts for only 13.5% of travel time, the emissions contribution is 24.1% for HC, 50.6% for CO, 30.0% for NOx, and 27.8% for $CO_2$. This underscores the need to ensure that the high speed/high VSP bins are well-represented in any database used to generate emission factors for MOVES.

## 4.4 Comparison of IM147 Emissions of $CO_2$, HC, CO, and NOx Predicted for 1994 and 1995 Model-Year Vehicles Using the MOVES Methodology to Actual IM147 Emissions

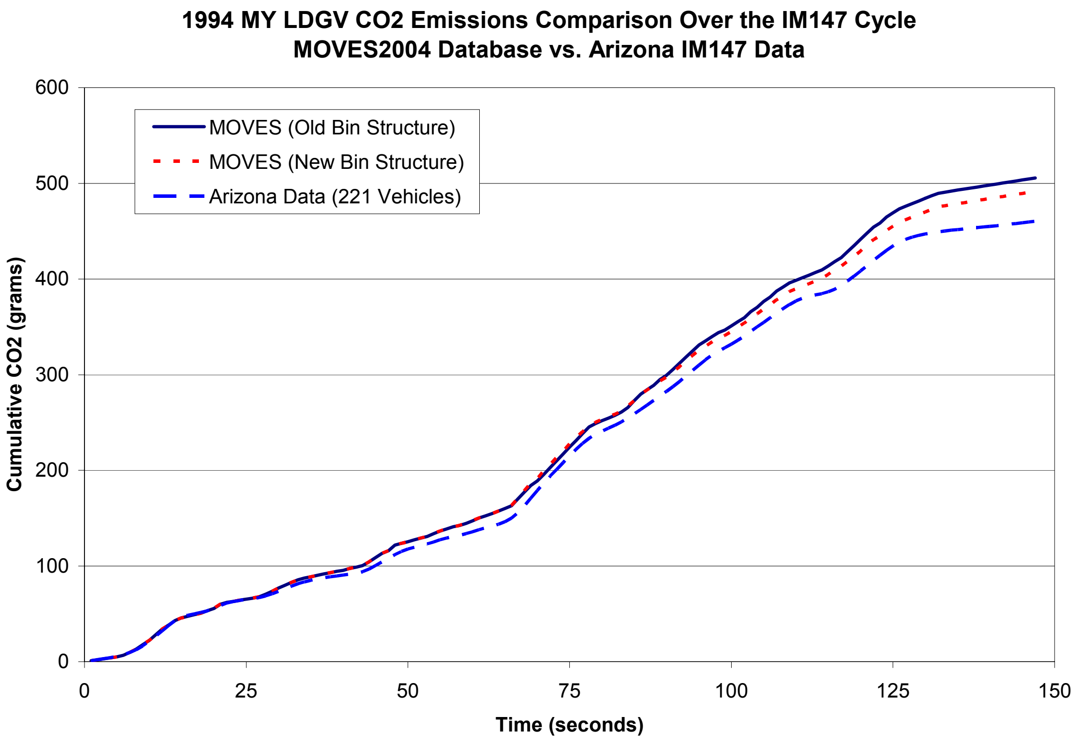
In order to evaluate the performance of the MOVES methodology in predicting emissions, underlying second-by-second emissions data for the MOVES model were processed and compared to actual emissions data collected from vehicles that were emissions tested in Arizona. This comparison was performed for 1994 and 1995 model-year light-duty gasoline powered vehicles because they are equipped with relatively advanced emission control systems and are well represented in the MOVES database—there are 1607 vehicles for the 1994 model year and 1584 for 1995. Emissions results from these tests were then averaged by model year and vehicle-specific-power (VSP) bins and applied to the IM147 drive trace to predict second-by-second emissions of $CO_2$, HC, CO, and NOx using the MOVES methodology. The second-by-second emissions data for these vehicles were "binned" using the current MOVES2004 binning structure as well as the "new" binning structure proposed by EPA for criteria pollutants (see Table 4-3).

| Table 4-4<br>MOVES2004 National Default LDGV VSP Operating Mode Bin Distribution<br>and Corresponding Emissions Contribution | | | | | |
|---|---|---|---|---|---|
| Operating Mode Bin | Time in Each Bin | Emissions Contribution | | | |
| | | HC | CO | NOx | $CO_2$ |
| 0 (Braking) | 8.8% | 3.9% | 1.4% | 1.4% | 2.9% |
| 1 (Idle) | 13.9% | 8.0% | 3.3% | 1.5% | 4.3% |
| Speed < 25 mph | | | | | |
| 11 (< 0)[a] | 6.0% | 4.8% | 1.7% | 2.5% | 2.7% |
| 12 (0-3) | 8.4% | 7.5% | 3.1% | 4.9% | 4.9% |
| 13 (3-6) | 4.0% | 5.7% | 2.4% | 4.5% | 3.6% |
| 14 (6-9) | 2.0% | 3.8% | 1.5% | 3.3% | 2.3% |
| 15 (9-12) | 1.7% | 3.2% | 1.5% | 3.3% | 2.5% |
| 16 (> 12) | 1.0% | 1.5% | 1.0% | 2.2% | 1.8% |
| Speed = 25-50 mph | | | | | |
| 21 (< 0) | 4.9% | 2.7% | 1.4% | 1.7% | 2.6% |
| 22 (0-3) | 5.1% | 3.4% | 1.5% | 2.7% | 3.5% |
| 23 (3-6) | 4.2% | 3.5% | 1.6% | 3.2% | 3.8% |
| 24 (6-9) | 3.6% | 3.5% | 2.0% | 3.9% | 4.3% |
| 25 (9-12) | 2.8% | 2.9% | 2.1% | 4.4% | 4.4% |
| 26 (> 12) | 4.1% | 8.6% | 10.9% | 14.9% | 9.8% |
| Speed > 50 mph | | | | | |
| 33 (< 6) | 7.5% | 5.9% | 6.1% | 5.1% | 6.7% |
| 35 (6-12) | 8.4% | 6.8% | 7.9% | 10.5% | 12.0% |
| 36 (> 12) | 13.5% | 24.1% | 50.6% | 30.0% | 27.8% |
| Total | 100% | 100% | 100% | 100% | 100% |

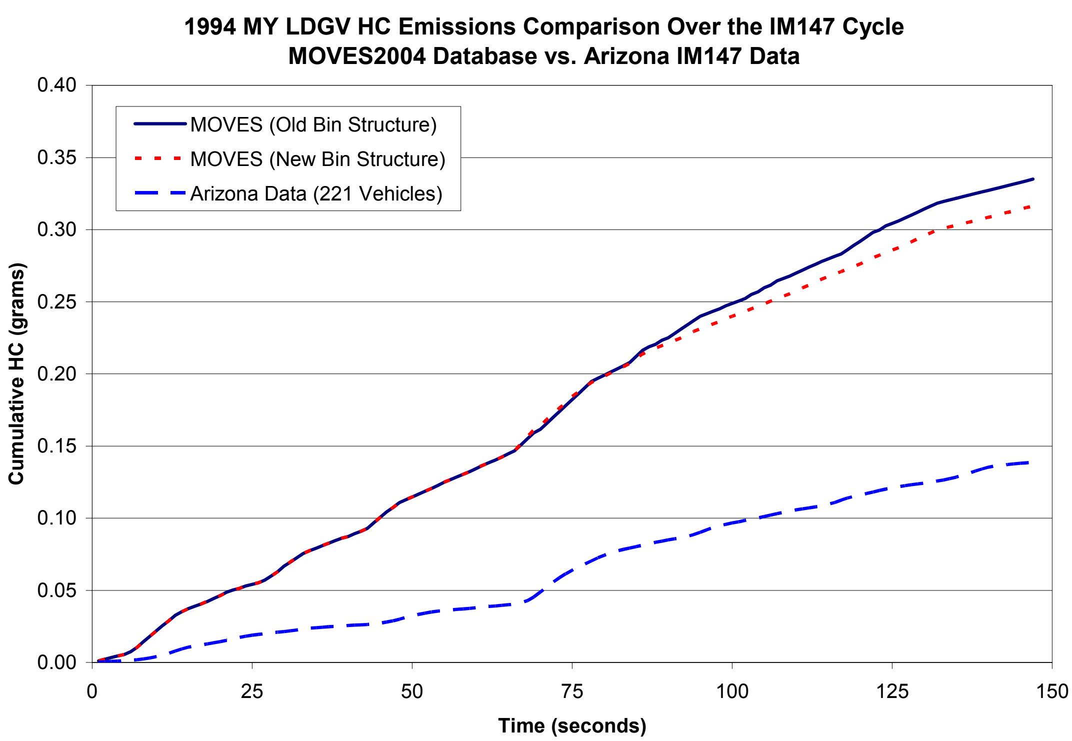
[a] Numbers in parentheses reflect the VSP range in units of kW/tonne.

These predicted emissions results were then compared to actual second-by-second emission measurements made over the IM147 drive cycle on a fleet of vehicles tested in Arizona.[3] Because the Arizona sample was not included in the development of the MOVES2004 database, it serves as a good test sample with which to compare and validate the results obtained using the MOVES2004 data and methodology. During the Arizona study, each of the vehicles was administered triplicate, back-to-back IM147 tests. Only the third IM147 test was used in this analysis to avoid issues associated with vehicle preconditioning. Data were available for 221 and 54 1994 and 1995 vehicles, respectively. The results of the comparison are presented in Figures 4-5 to 4-8 for 1994 vehicle emissions of $CO_2$, HC, CO and NOx, respectively and the 1995 model-year results are similarly presented in Figures 4-9 to 4-12.

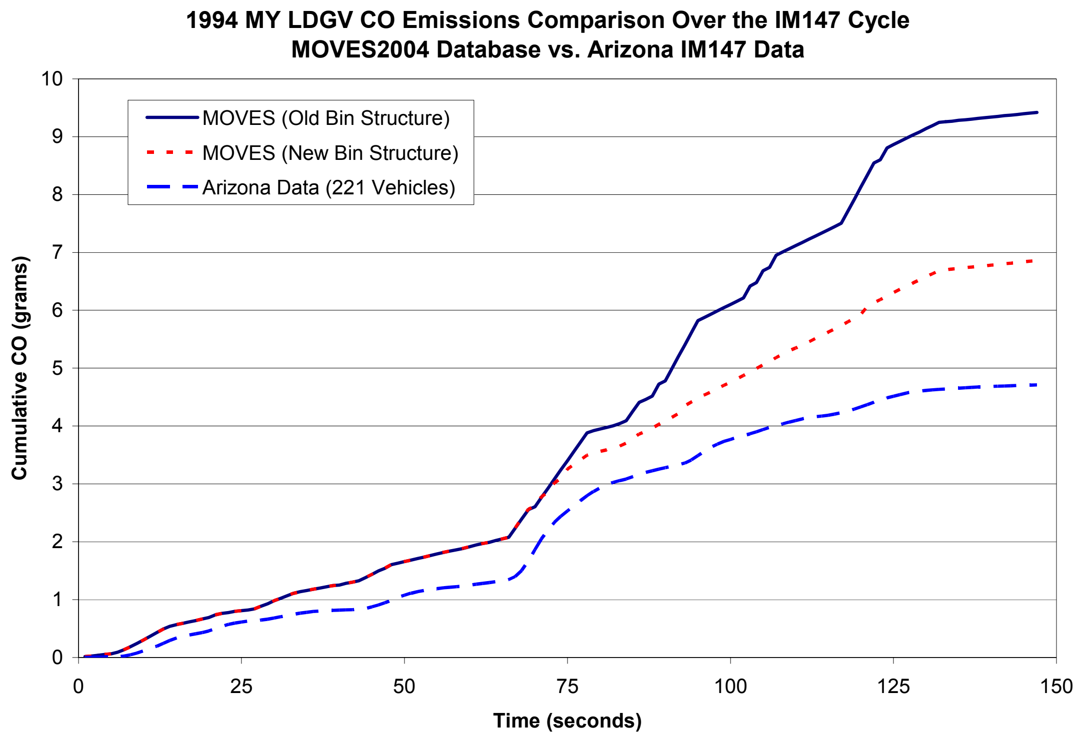
## Figure 4-5



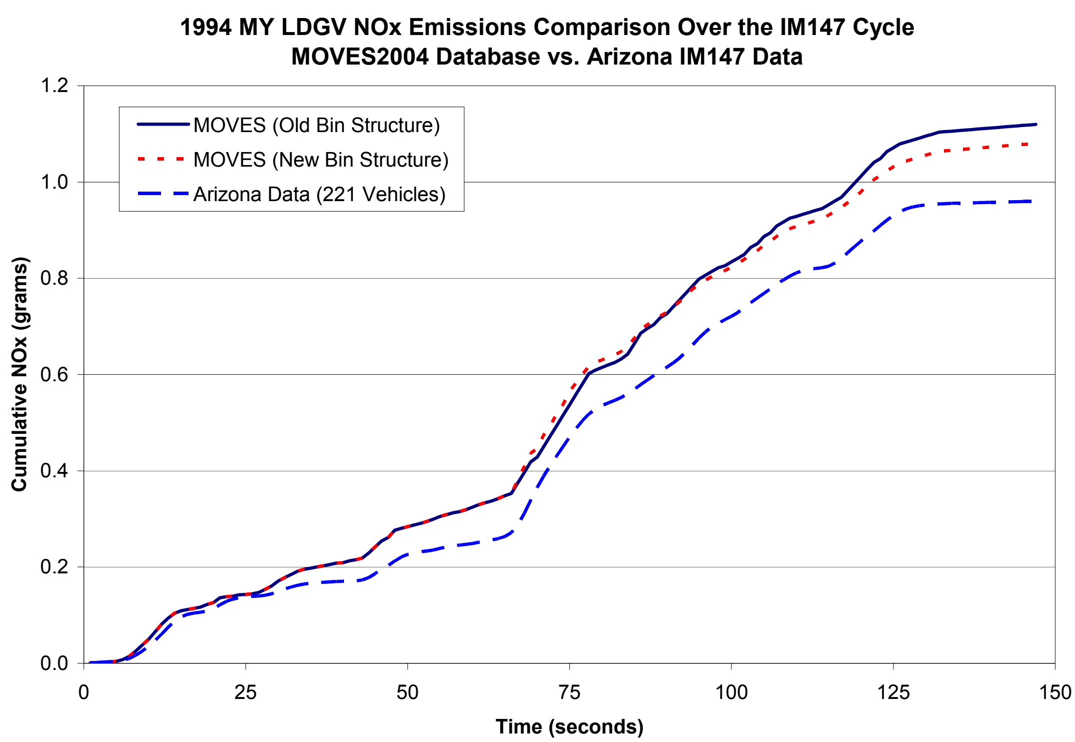

## Figure 4-6



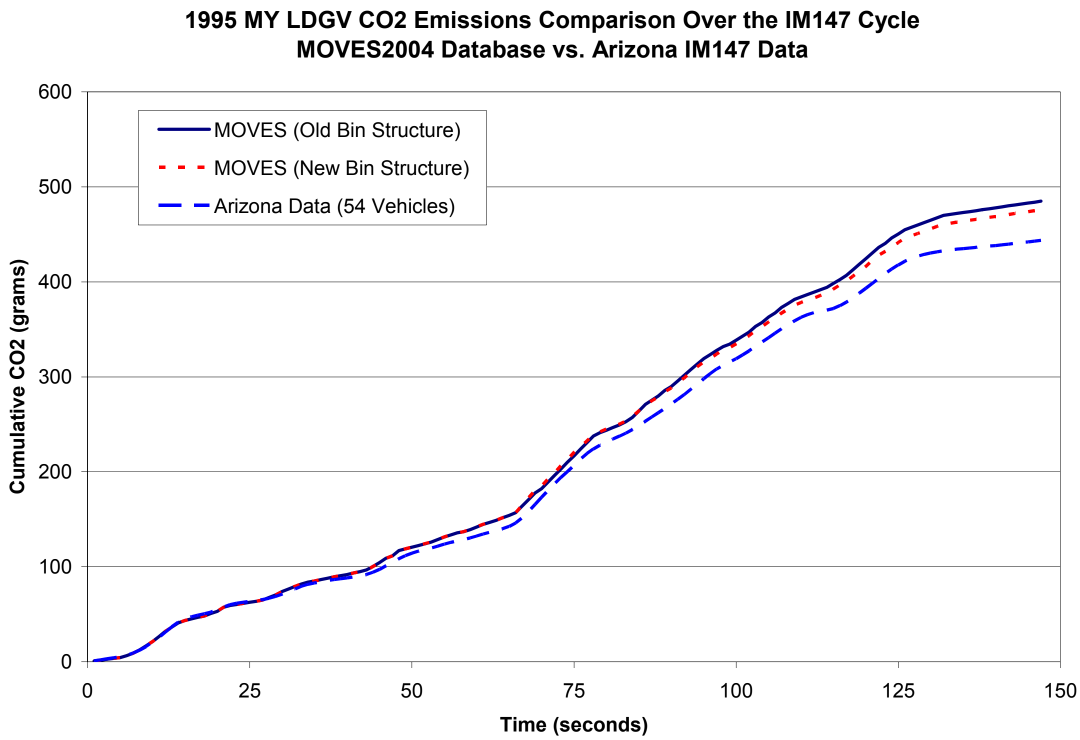
## Figure 4-7




## Figure 4-8



## Figure 4-9




## Figure 4-10

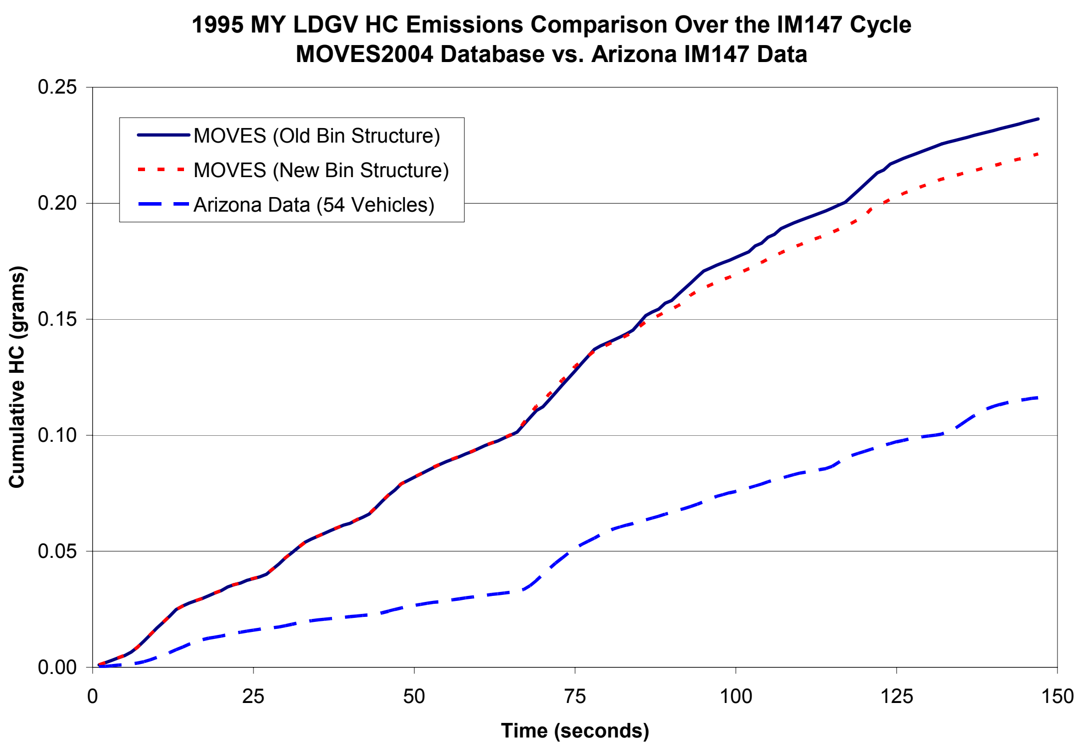


**Figure 4-11**

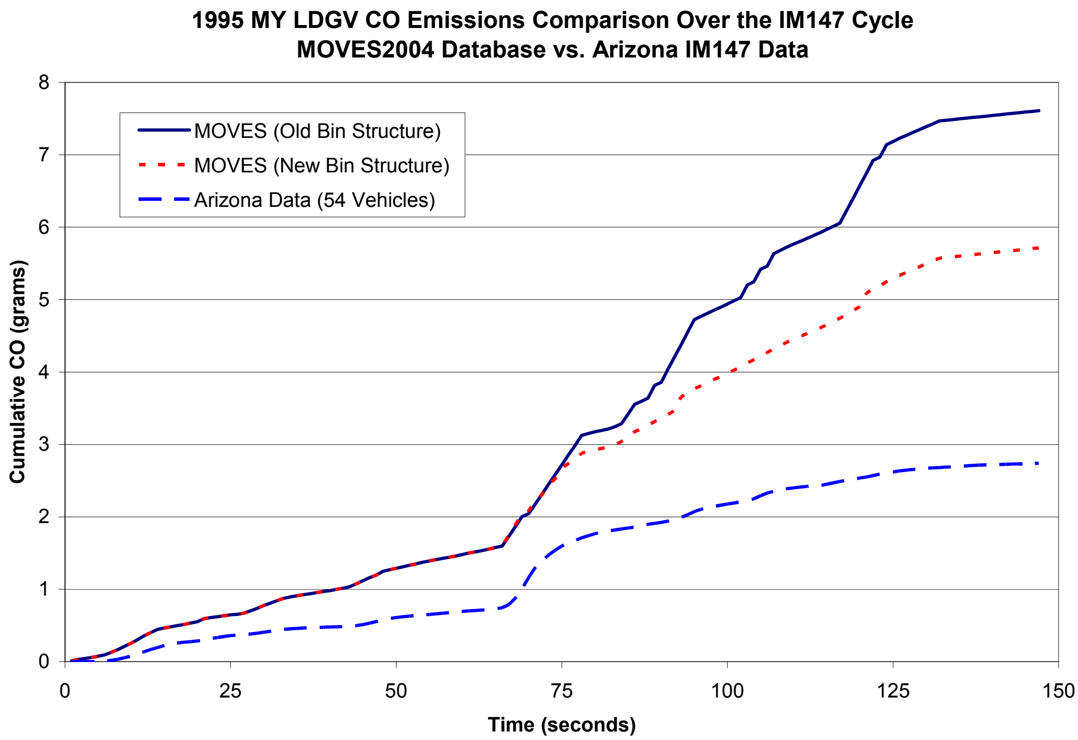
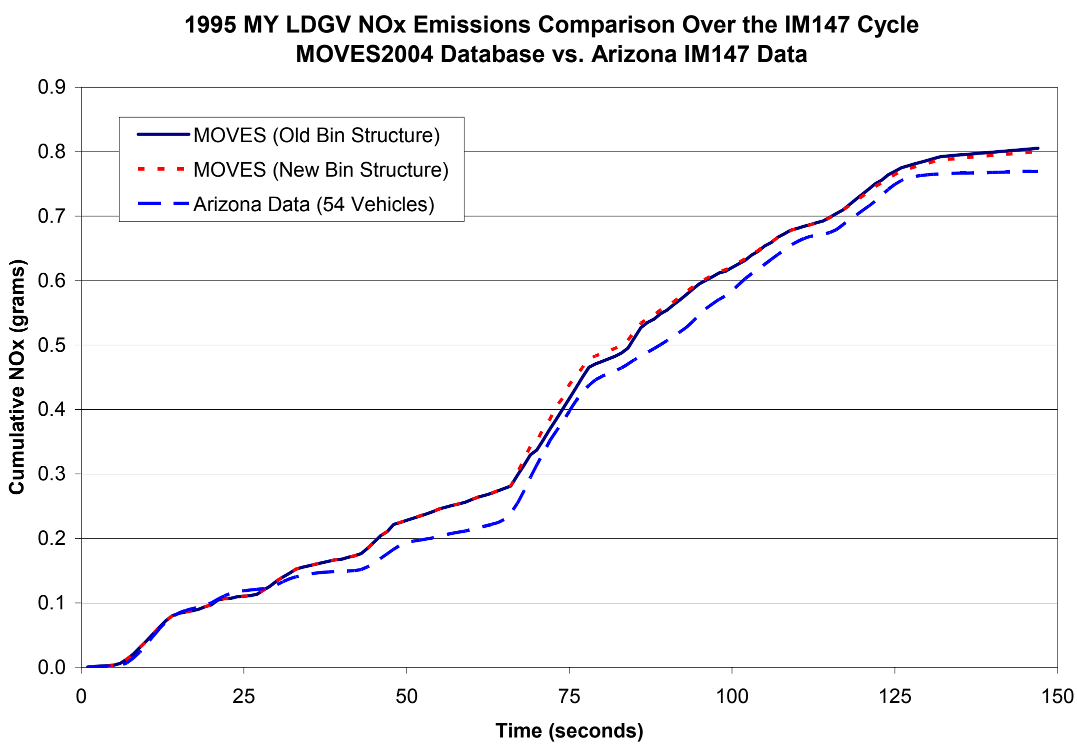



**Figure 4-12**



As shown in Figures 4-5 to 4-12, the MOVES methodology consistently overpredicts IM147 emissions of all four pollutants for both the 1994 and 1995 model-year vehicles, although better agreement is shown using the "new" bin structure. The best agreement between the MOVES predictions and actual emissions is observed for $CO_2$ and NOx, where cumulative emission values are within about 10%. The actual emissions of HC and CO are between 2 to 3 times lower than those predicted using either MOVES methodology. The poor agreement of the HC and CO results strongly suggests that there will be significant issues associated with the accuracy of criteria pollutant emissions using the MOVES methodology, particularly when one considers that the bulk of the data in the MOVES database was obtained from vehicles tested using the IM240 driving cycle.[*]

There are a number of potential reasons for the inconsistencies observed in the above figures. Most notably, the vehicle fleets used in the two analyses are different, although both were randomly selected for participation in each program. The MOVES2004 database is largely represented by vehicles tested in New York in the 1999 to 2002 timeframe. On the other hand, the Arizona IM147 sample was collected in the 1998 to 1999 timeframe. Thus, one might expect differences in the degree of emission control system deterioration between the two samples, and therefore higher emissions from the MOVES2004 estimates. However, it is very unlikely that deterioration alone is leading to the two- to three-fold difference in HC and CO emissions observed in the above figures. Other issues that could be contributing to the differences above include the following:

- *Gasoline Specifications* - Each program tested vehicles with tank fuel, and there could be differences between New York and Arizona gasoline. However, a review of Alliance fuel survey data showed similarities in sulfur and oxygenate content in the 1999 summertime Arizona fuel and the 2001 summertime New York fuel.

- *Preconditioning* - As noted above, the Arizona IM147 data were collected as part of a triplicate IM147 test protocol. In this analysis, the third test was used and therefore each vehicle was fully preconditioned. It is unclear what protocol was used to ensure the New York IM240 tests were fully preconditioned, but if those vehicles were not fully preconditioned, that would help explain some of the difference observed in the HC and CO results.

- *Inconsistencies in the MOVES2004 Modal Modeling Approach* - Ultimately, the differences in HC and CO emissions estimates presented in the above figures could be a result of inconsistencies and inaccuracies associated with the application of the MOVES2004 modal modeling approach to criteria pollutant emissions. <u>Although very good agreement is observed in the $CO_2$ estimates, it is</u>

[*] Note that the IM147 test procedure is a subset of the IM240, consisting of the final 147 seconds of the IM240. Thus, one would expect good agreement between the Arizona sample and the MOVES2004 database and methodology.

important not to use those favorable results to assume that this approach is necessarily valid for criteria pollutant emissions estimates.

## 4.5 Comparison of MOVES Predictions of Criteria Pollutants With MOBILE6 Predictions

In addition to comparing MOVES predictions of criteria pollutant emissions to actual emissions data, we compared those predictions to estimates generated by MOBILE6. The comparisons were again made for 1994 and 1995 model-year vehicles using both the current and "new" MOVES bin structures. In this comparison, two driving cycles were used to generate both MOVES and MOBILE6 estimates. These were the non-freeway LOS A/B (average speed of 24.8 mph) and freeway LOS D (average speed of 52.9 mph) cycles described in the MOVES documentation.* The MOBILE6 modeling runs were made for January 1, 1999, at 75°F with a 9 RVP, 30 ppm sulfur gasoline. Using these inputs, correction factors are not applied to account for temperatures and fuels outside of FTP conditions. Thus, the comparisons presented below are very simplistic in that corrections for non-standard conditions are not applied. Runs were made both with and without an I/M program, where the I/M program was assumed to be the most stringent modeled by MOBILE6—an annual centralized program based on IM240 testing.

The results of these comparisons are shown in Tables 4-5 and 4-6 for the LOS A/B and LOS D driving cycles, respectively. As shown in Table 4-5, agreement between the MOVES and MOBILE6 predictions is reasonable, with better agreement being observed for the no-I/M MOBILE6 results. As expected given the relatively low speed of this cycle, the new binning structure has a relatively minor impact on the results.

**Table 4-5**
**Comparison Between MOVES and MOBILE6.2 Emission Factors (Units = g/mi)**
**Automobiles on Arterial LOS A/B Driving Cycle (Average Speed = 24.8 mph)**

| Pollutant | Model Year | MOVES (Current Bin Approach) | MOVES (New Bin Approach) | MOBILE6.2 I/M | MOBILE6.2 No I/M |
|---|---|---|---|---|---|
| THC | 1994 | 0.30 | 0.29 | 0.17 | 0.27 |
| | 1995 | 0.20 | 0.20 | 0.14 | 0.20 |
| CO | 1994 | 5.73 | 4.90 | 4.89 | 6.58 |
| | 1995 | 4.62 | 3.98 | 4.03 | 5.09 |
| NOx | 1994 | 0.81 | 0.79 | 0.64 | 0.76 |
| | 1995 | 0.61 | 0.60 | 0.51 | 0.59 |

* MOBILE6 could not be used to estimate emissions on the IM147 cycle because it does not include any estimates for that cycle. The comparison was therefore made for two cycles that are estimated by MOBILE6.

| Table 4-6<br>Comparison Between MOVES and MOBILE6.2 Emission Factors (Units = g/mi)<br>Automobiles on Freeway LOS D Driving Cycle (Average Speed = 52.9 mph) | | | | | |
|---|---|---|---|---|---|
| Pollutant | Model Year | MOVES (Current Bin Approach) | MOVES (New Bin Approach) | MOBILE6.2 I/M | MOBILE6.2 No I/M |
| THC | 1994 | 0.16 | 0.15 | 0.19 | 0.23 |
| | 1995 | 0.11 | 0.11 | 0.15 | 0.17 |
| CO | 1994 | 6.62 | 5.05 | 6.72 | 8.55 |
| | 1995 | 5.38 | 5.03 | 5.68 | 6.82 |
| NOx | 1994 | 0.61 | 0.60 | 0.69 | 0.75 |
| | 1995 | 0.40 | 0.40 | 0.51 | 0.64 |

The results shown in Table 4-6 for the higher speed LOS D cycle show that MOBILE6 predicts higher emissions of all three pollutants both with and without I/M than does MOVES using either binning strategy. The magnitude of the difference between the MOBILE- and MOVES-based predictions is on the order of 30% for NOx and 40% for HC and CO emissions. As expected, the effects of the new MOVES bin structure are more apparent with CO emissions evaluated with the higher speed cycle.

It may be appealing to use the comparisons presented in the tables above to draw conclusions regarding the efficacy of the MOVES modal approach to estimate emissions from the in-use vehicle fleet; however, one must be cautious in making that leap. Although the MOBILE6-based emission rates match those generated with the MOVES2004 database and methodology reasonably well, there are no assurances that the MOBILE6-based estimates represent the "gold standard" for comparison. We continue to believe that the best validation of the MOVES2004 data and methodologies is that performed with an independent set of data such as the Arizona IM147 sample evaluated above. And, as noted above, the MOVES2004 approach resulted in a significant overestimate of IM147 HC and CO emissions from that sample.

## 4.6 Summary of Issues Associated with Estimating Criteria Pollutant Emissions Using the MOVES Methodology

The MOVES methodology is predicated on the assumption that vehicles in a given source bin accurately reflect the characteristics of in-use vehicles of the same type. While this assumption is important with respect to fuel consumption, it will be of critical importance with respect to the estimation of criteria pollutants. Of key importance will be the distribution of normal and high emitting vehicles within each source bin. It is our understanding that EPA plans to address this issue by collecting vast amounts of data from in-use vehicles using portable emissions monitors (PEMs). It is not clear, however, when an adequate amount of data will be available or, even after such data are collected, that the distribution of high and normal emitting vehicles in each source bin will accurately reflect the situation in different regions of the country.

Another important issue is how fuel composition impacts on emissions will be addressed in versions of the MOVES model that estimate criteria pollutant emissions. At present, there is no information regarding fuel composition associated with much of the second-by-second data in the MSOD. Given the lack of fuel composition information, it will be difficult to account for the impact of the Tier 2 gasoline sulfur limit on criteria pollutant emissions using the MOVES methodology. Additionally, it is likely that fuel effects will be treated as a simple multiplicative correction factor in a criteria pollutant version of MOVES. However, the benefits of certain fuel programs (e.g., oxygenated fuels) would be expected to have a greater impact during certain operating modes than others (e.g., during enrichment events), but it is extremely unlikely that sufficient data would be available to generate estimates of fuel effects by VSP operating mode bin. This same general idea can be extended to other correction factors that are routinely applied in MOBILE-based models to account for nonstandard conditions—data generally do not exist to allow correction factors to be developed as a function of operating mode bin.

Finally, our comparison of the Arizona IM147 data to a MOVES-based criteria pollutant analysis showed reasonable agreement between NOx and $CO_2$ emissions. However, large differences were observed for HC and CO emissions, with the MOVES-based analysis predicting emissions that were roughly two times those observed in the data sample. As outlined above, some of that difference may be attributable to differences in emission control system deterioration characteristics (i.e., the distribution of high and normal emitters in each fleet) between the Arizona IM147 sample and the MOVES2004 sample. However, that alone does not sufficiently explain the differences. Ultimately, these differences could be a result of inconsistencies and inaccuracies associated with the application of the MOVES2004 modal modeling approach to criteria pollutant emissions. Although very good agreement is observed in the $CO_2$ estimates, it is important not to use those favorable results to summarily assume that this approach is necessarily valid for criteria pollutant emissions estimates.

Given the issues outlined above, it is very unlikely that a MOVES-based model will be able to predict criteria pollutant emissions with any improved performance over a MOBILE-based model. The improved flexibility of a modal model (e.g., the ability to model any drive cycle) is likely to come at the expense of increased uncertainty in the emissions estimates.

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# 5. REVIEW OF THE MOVES2004 PHYSICAL EMISSION RATE ESTIMATOR (PERE)

The Physical Emission Rate Estimator, or PERE, model is a key component of MOVES2004. It was used by EPA to develop default energy inputs in MOVES2004 for portions of the vehicle fleet not covered in EPA's current database and to forecast energy consumption estimates for future technology vehicles. The PERE model is reviewed in this section of the report. Elements of the review include a general overview of the model and its inputs, evaluations of the approach used by PERE to model both existing and advanced engine technologies, analysis of PERE's ability to model criteria pollutants, and a review of earlier comments regarding PERE that were submitted to EPA.

## 5.1 Overview of PERE and Its Primary Inputs

Basic Model Formulation - PERE is a spreadsheet-based model that calculates the energy (i.e., fuel consumption) required by a vehicle to follow an input second-by-second driving trace. It calculates the power demand needed to follow the driving trace at each second by overcoming inertia, road grade, tire friction, and aerodynamic loss based on the following equation:

$$P_b = VSP \times m = mv[a(1+\varepsilon) + g \times grade + g \times C_R] + 0.5\, \rho\, C_D A_F v^3$$

where

- $P_b$ is brake (i.e., tractive) power (in watts);
- $VSP$ is vehicle specific power (power per unit mass);
- $m$ is mass (in metric tons);
- $v$ is vehicle speed (in m/s);
- $a$ is vehicle acceleration (in m/s$^2$);
- $\varepsilon$ is rotational mass factor (~0.1);
- $g$ is gravitational acceleration constant (9.81 m/s$^2$);
- $grade$ is road grade
- $C_R$ is coefficient of rolling resistance (~0.009);
- $\rho$ is air density (~1.2 kg/m$^3$)
- $C_D$ is aerodynamic drag coefficient (~0.3); and
- $A_F$ is vehicle frontal area (~ 2 m$^2$).

When supplied by the user for a specific vehicle simulation, PERE uses dynamometer coastdown coefficients A, B, and C (representing rolling, rotating and aerodynamic coefficients, respectively) to calculate brake power as a function of the speed and acceleration required by an input driving trace as follows:

$$P_b = mv[a + g \times grade] + Av + Bv^2 + Cv^3$$

These equations and their ability to represent second-by-second power required at the wheels to follow any driving trace are well established in the literature. How PERE translates this power demand to predicted second-by-second fuel consumption is the key to understanding its capabilities and limitations. In short, PERE uses a series of empirically derived relationships to calculate fuel consumption as a function of power demand. The methods used by PERE to calculate fuel consumption for existing internal combustion (IC) engine technology and advanced technologies are discussed separately below.

<u>Existing IC Technology Fuel Consumption</u> – For current (i.e., existing) IC engines, PERE makes a critical assumption that engine efficiency can be accurately estimated from a simple linear relationship between brake mean effective pressure (BMEP) and a term called "fuel mep" (defined as k + BMEP/$\eta$, where k is a constant and $\eta$ is engine efficiency). The model therefore assumes that engine speed and factors affecting engine speed (such as gearing and shift logic) are not relevant. However, actual engine maps indicate that, at constant BMEP, the efficiency of real engines varies by as much as 40% or more. This is one reason why EPA's assertion that light-duty vehicles are "not very sensitive to transmission" is incorrect. Depending on the driving cycle, differences in lockup strategies, gear spacing, and shift logic can affect energy use by nearly 10%.

Notwithstanding the limitation described above, the PERE model can produce reasonable estimates of fuel consumption for conventional, gasoline-fueled vehicles. As shown in the next sub-section, the reasonableness of the PERE fuel consumption estimates begins to falter for driving cycles that contain higher speeds and more aggressive accelerations than contained in the FTP (City/Urban) and Highway Fuel Economy Test (Highway) driving cycles. This is due to the greater presence of events at or near wide open throttle under which PERE's assumed linear BMEP vs. FMEP relationship is invalid.

<u>Advanced Technology Fuel Consumption</u> – In the PERE model, EPA defines "advanced" technology as a vehicle or component that is improved over those in most current vehicles. Practically, this represents vehicle technologies that are not represented in the MSOD/MOVES database and includes lean-burn gasoline engines, variable displacement (e.g., variable valve lift and timing, VVLT), direct gasoline injection and continuously variable transmissions (CVTs) and hybrid-electric vehicles. (It should be noted that a number of these "advanced" technologies already exist in the marketplace. For example, VVLT and CVT on the 2004 and newer BMW745i, cylinder deactivation on the 2005 Chrysler 300C and hybrid-electric in the 2000 and newer Honda Insight and 2001 and later Toyota Prius.)

Although the PERE model is capable of producing reasonable fuel consumption estimates for conventional technologies, the results it predicts for more advanced technologies are prone to larger errors. The fundamental problem with the way PERE handles advanced IC technologies is that it assumes they can be modeled by using a uniform improvement in engine efficiency:

> *For the "generic" advanced internal combustion (AIC) engine vehicle in MOVES, PERE uses target coefficients, rather than choosing a suite of specific technologies. These target values are assumed to be a 10% improvement in indicated efficiency (0.44), and engine friction equivalent of 2015 (Figure 21).*

However, increasingly popular technologies like cylinder deactivation and variable valve lift and timing do <u>not</u> increase efficiency uniformly over the full range of engine operation. For example, cylinder deactivation improves efficiency only at light loads. At higher loads, the engine runs just like an engine that does not have a cylinder deactivation system. It should also be noted that cylinder deactivation is usually turned off at idle to prevent the engine from running too roughly. Like cylinder deactivation, variable valve lift and timing primarily improves efficiency at light loads.[*] Unlike cylinder deactivation, VVLT does not need to be deactivated at idle.

The non-uniform effect of technologies like cylinder deactivation and VVLT explains the results presented above. On driving cycles with higher power demand, the fuel economy benefits are less than on cycles with low power demand. Because PERE assumes a uniform increase in engine efficiency, it overstates the benefits of such technologies on driving cycles requiring higher engine load.

There are also problems with the manner in which PERE is used to model hybrid vehicles. EPA assumes that hybrid vehicles will be "launched" using only their electric motor(s) to the extent that power demand is lower than the rated capacity of the electric motors. While this approach to modeling hybrids may sound superficially appealing, it is not valid. The Prius vehicle that EPA cites as an example is a case in point. As EPA notes, the Prius has a high ratio of electric motor power to combustion engine power; however, EPA's proposed approach to modeling a "full hybrid" vehicle like the Prius fails to account for the fact that the available battery power is substantially less than the available electric motor power. To use the full rated power of the electric motors, it is necessary to run the combustion engine and spin the generator. The "no charging while engine running" assumption is also a simplification that is inconsistent with the way hybrids are actually programmed. Because of these problems and the above-mentioned problems with the way engine efficiency is estimated, it is not surprising that the material EPA has presented regarding "City Fuel Economy Validation" shows poor predictions of hybrid vehicle fuel economy. EPA's conclusion that the hybrid fuel economy validation is "robust" is inconsistent with the actual data EPA has presented.

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[*] It should be noted, however, that sophisticated VVLT systems can also increase peak power per cubic inch, allowing a smaller engine to be used to achieve the target horsepower. The engine downsizing leads to improved fuel economy across the full range of engine operation.

Primary Inputs to PERE – PERE is a spreadsheet model that uses a series of interrelated worksheets to accept user inputs, perform energy consumptions calculations, and report results. The primary vehicle-related inputs to PERE are listed below.

- Model year
- Weight
- Engine displacement
- Road load (A, B, C / Fa, Cd, Cr / TRdLd)
- Indicated engine efficiency
- Technology type (conventional, hybrid, electric, fuel cell)
- Fuel type (gasoline, Diesel)
- Transmission type (auto or manual)
- Vehicle type (PC or LDT)

In addition to these vehicle-related inputs, the second-by-second driving schedule being modeled is input in a separate sheet. A number of other default parameters in PERE's primary inputs worksheet (called GUI)—such as transmission gearing and shift points, fuel parameters (e.g., density) and battery and motor characteristics for hybrids—can also be overridden.

## 5.2 Modeling of Existing Internal Combustion Technology

Existing Technology Measurements - The accuracy of PERE's fuel consumption estimates for existing IC technologies was assessed by performing a series of comparisons to actual fuel consumption measurements for a sample of late-1990s model year light-duty vehicles over several driving cycles. The measurements were made on Sierra's chassis dynamometer under a 2002 light-duty vehicle testing study[4] performed jointly for the California Air Resources Board (CARB) and the California Department of Transportation (Caltrans). Under this study, emissions were measured for 44 late model light-duty gasoline vehicles over a series of transient driving cycles that included the FTP, CARB's Unified or LA92 cycle (UC), and a set of freeway cycles developed from real-world driving data under a companion study that represent light-duty vehicle operation on freeways under different levels of congestion. Second-by-second constant volume samples of THC, CO, $CO_2$, and NOx were collected under the testing program. Post-processing was performed to account for tailpipe-to-analytical bench travel time and calculate second-by-second mass emissions and carbon balance-based fuel consumption.

A total of three vehicles were selected from this measurement database for the PERE evaluation to represent a range of light-duty vehicle power and weight characteristics:

1. 1998 Toyota Camry LE (light, small engine passenger car);
2. 1999 Ford Taurus SE (mid-sized passenger car); and
3. 1999 Chevrolet Suburban (large SUV).

Table 5-1 lists detailed characteristics for each of these three vehicles.

**Table 5-1**
**Case Study Vehicle Characteristics**

| Parameter | 1998 Toyota Camry LE | 1999 Ford Taurus SE | 1999 Chevrolet Suburban |
|---|---|---|---|
| Eng Size (lit) | 2.2 | 3.0 | 5.7 |
| # Cylinders | I4 | V6 | V8 |
| Horsepower (hp) | 133 | 145 | 255 |
| Valves per Cylinder | 4V | 2V | 2V |
| Transmission | 4-Spd Auto | 4-Spd Auto | 4-Spd Auto |
| Rear Axle Ratio | 3.93 | 3.77 | 3.42 |
| Curb Wt (lb) | 3,120 | 3,326 | 4,769 |
| Equivalent Test Weight (lb) | 3,375 | 3,625 | 6,500 |
| Aero. Drag Coefficient (Cd) | 0.300 | 0.300 | 0.434 |
| Tire Size | 195/70/14 | 205/65/15 | 235/75/15 |
| Rolling Radius (ft) | 0.990 | 1.020 | 1.155 |
| Length (in) | 188.5 | 197.5 | 219.5 |
| Width (in) | 70.1 | 73.0 | 76.7 |
| Height (in) | 55.4 | 55.1 | 71.3 |
| Rolling Friction Coefficient ($C_R$) | 0.0109 | 0.0105 | 0.0103 |
| Frontal Area ($ft^2$) | 22.5 | 24.3 | 32.0 |
| Track Road Load HP @50 mph | 12.1 | 13.0 | 16.7 |

For the PERE evaluation, fuel consumption was estimated over three separate driving cycles tested under this earlier study:

1. FTP Urban or City driving cycle;
2. CARB UC cycle; and
3. Uncongested Freeway (LOS A) driving cycle.

These cycles were specifically selected to examine the performance of PERE under a range of driving patterns. The FTP is a 1371-second cycle developed from travel over a road route in urban Los Angeles over 30 years ago and has been used by EPA since that time to measure in-use vehicle emissions and fuel economy (in conjunction with the Highway cycle). In part due to dynamometer capabilities at that time, the FTP driving cycle was developed with mild or low acceleration rates. Both EPA and CARB have recognized that the FTP cycle no longer represents driving patterns of today's light-duty vehicle fleet. The UC cycle was developed by CARB in 1992 to represent more recent urban driving patterns and include higher speeds and acceleration rates than found in the FTP. Finally, the LOSA cycle was developed from driving data collected in 2002 on freeways under Level of Service "A" or uncongested conditions as defined in the Highway Capacity Manual.[5] This LOS A cycle was based on very recent data collected since the 1995 repeal of the federal 55-mph speed limit. It contains high speeds and aggressive accelerations that are more typical of today's higher power-to-weight ratio vehicle fleet. Table 5-2 compares summary statistics for each of these three driving cycles.

**Table 5-2**
**Comparison of Selected Driving Cycles**

| Statistic | FTP Urban (City) | Unified (UC) | Freeway LOSA |
|---|---|---|---|
| Time (minutes) | 22.85 | 24.15 | 6.65 |
| Distance (miles) | 7.45 | 10.00 | 7.51 |
| Average Speed (mph) | 19.6 | 24.8 | 67.8 |
| Minimum Speed (mph) | 0.0 | 0.0 | 55.6 |
| Maximum Speed (mph) | 56.7 | 67.2 | 79.5 |
| Maximum Acceleration (mph/s) | 3.3 | 6.9 | 1.6 |
| Average Positive Power per unit mass ($mph^2/s$) | 7.66 | 32.66 | 39.38 |

In the 2002 testing study, the City cycle was driven from a cold start following an overnight soak, and, as under the FTP, the first 505 seconds of the trace were then repeated as a Hot-505 test. The other two cycles were run while the vehicles were fully warmed up. Since PERE does not account for the effects of a cold start on fuel consumption, measured results for the City cycle presented in this evaluation are based on a Hot-Urban (Bag 3 + Bag 2) test.

<u>VEHSIM Modeling</u> - In addition to comparing PERE estimates to actual measurements for these vehicles and driving cycles, fuel consumption was estimated using a more robust vehicle simulation model called VEHSIM. VEHSIM was originally developed by General Motors and became public domain during the 1980s.[*] Since that time, Sierra has continuously refined VEHSIM to support a range of driving pattern and fuel economy studies.

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[*] VEHSIM is a vehicle simulation model originally developed by General Motors Corporation and substantially modified by Sierra Research. The model calculates the instantaneous power required to propel a vehicle over any specified driving cycle based on user-supplied information regarding road surface, wind speed, roadway grade, vehicle weight, frontal area, aerodynamic drag coefficient, rolling resistance, and rotational inertia of the engine and other drivetrain components. The engine speed and load required to supply the required power is calculated from information regarding rolling radius, tire rolling resistance, axle ratio and axle efficiency, transmission gear ratios and efficiency, shift logic, torque converter characteristics and lockup schedule, and accessory power demand. Instantaneous fuel consumption is calculated by interpolation of the individual data points on an "engine map" (i.e., fuel consumption as a function of speed and load). The engine maps available for use with VEHSIM include "blended" maps for conventional engines supplied by Alliance member companies and maps for alternative engines extracted from the technical literature. The VEHSIM model can usually estimate the fuel economy of a typical passenger car within a few percent of measured CAFE results. EPA is familiar with the VEHSIM model because the routine incorporated in the model to estimate the increase in fuel consumption associated with cold start and warmup operation was actually developed by Sierra under contract to EPA.

Unlike the more simplistic PERE model, VEHSIM can accurately represent a wide variety of technologies. Detailed specifications of the vehicle design and the driving conditions are inputs to VEHSIM. The user specifies vehicle weight, frontal area, drag coefficient, and other parameters affecting the power required to maintain the specified speed-time profile. The user also selects from a collection of "parts," which represent alternative choices in power train components. These parts represent the engine, engine accessories, transmission torque converter, transmission gear set, transmission shift logic, axle ratio, and tires.

Based on the specified vehicle design, VEHSIM calculates the instantaneous power at the drive wheels required to maintain the specified speed-time profile similarly to PERE. However, unlike PERE's empirical approach to translating wheel power back through the drivetrain to the engine to calculate engine power and fuel consumption, VEHSIM explicitly treats the forces and energy transfer back to the engine. Based on the tire size, axle ratio, and axle efficiency, the drive wheel power and speed is translated into the speed and power required at the output of the transmission. Based on the transmission gearing, shift logic, torque converter speed ratio, and efficiency, the power and speed at the input of the transmission is computed. Total engine load is determined by adding accessory losses to the required transmission input. Finally, the instantaneous fuel consumption rate is determined from the engine "map," which is a detailed tabulation of fuel consumption as a function of speed and load. The fuel consumption is computed 20 times a second by interpolation between the individual data points contained on the map.

Summary of Existing IC Modeling – Table 5-3 compares fuel consumption estimates from both the PERE and VEHSIM models to actual measurements for the three late model light-duty vehicles typical of existing IC engine technology from the 2002 testing program.

Table 5-4 compares the relative error of the PERE and VEHSIM estimates to actual measurements for each vehicle. Average values of the relative error across all three vehicles (taking the absolute value for each vehicle to account for bias) for each model are shown at the bottom of the table. Table 5-4 shows that PERE produces reasonable estimates of measured fuel consumption for each vehicle examined on the Urban driving cycle. However, for the freeway LOS A cycle, PERE's fuel consumption estimates do not agree as well with actual measurements. This can be seen more clearly in the average error statistics shown at the bottom of Table 5-4. This finding is likely due to the greater presence of events at or near wide open throttle in the LOS A cycle under which PERE's assumed linear BMEP vs. FMEP relationship is obviously invalid.

| Table 5-3<br>**Comparison of Existing Technology Fuel Consumption Estimates** | | | | |
|---|---|---|---|---|
| | | Fuel Consumption (gal) | | |
| Vehicle | Source | Urban-Hot (City) | Unified (UC) | Freeway LOSA |
| Camry | Measured | 0.314 | 0.382 | 0.225 |
| | PERE | 0.285 | 0.401 | 0.242 |
| | VEHSIM | 0.252 | 0.362 | 0.228 |
| Taurus | Measured | 0.338 | 0.445 | 0.255 |
| | PERE | 0.338 | 0.462 | 0.275 |
| | VEHSIM | 0.308 | 0.423 | 0.256 |
| Suburban | Measured | 0.548 | 0.744 | 0.473 |
| | PERE | 0.583 | 0.785 | 0.416 |
| | VEHSIM | 0.565 | 0.766 | 0.453 |

| Table 5-4<br>**Comparison of Relative Error in Modeled Fuel Consumption Estimates for Existing Technology Vehicles** | | | | |
|---|---|---|---|---|
| | | Relative Error (% of Measured Fuel Consumption) | | |
| Vehicle | Model | Urban-Hot (City) | Unified (UC) | Freeway LOSA |
| Camry | PERE | 9.2% | -5.1% | -7.7% |
| | VEHSIM | 19.9% | 5.4% | -1.6% |
| Taurus | PERE | 0.0% | -3.8% | -7.7% |
| | VEHSIM | 8.8% | 4.8% | -0.2% |
| Suburban | PERE | -6.4% | -5.4% | 12.1% |
| | VEHSIM | -3.1% | -2.9% | 4.3% |
| Average | PERE | **5.2%** | **4.8%** | **9.2%** |
| | VEHSIM | **10.6%** | **4.4%** | **2.0%** |

## 5.3 Modeling of Advanced Technologies

In addition to the existing technology evaluation, PERE and VEHSIM model simulations were compared for both advanced IC technologies and hybrid technologies. Modeled estimates in this sub-section are compared to unadjusted CAFE fuel economy ratings for selected vehicles obtained from EPA at *http://www.fueleconomy.gov*. Thus comparisons below are expressed as fuel economy in miles per gallon rather than as fuel consumption in gallons.

Advanced IC Technologies – Two types of advanced IC technologies were examined: (1) variable valve lift and timing; and (2) cylinder deactivation (CDEACT). As pointed out earlier, these technologies already exist in the marketplace. The BMW745i includes an advanced continuous VVLT design in its Valvetronic engine that was introduced in model year 2004. Introduced in 2005, the Chrysler 300C employs a cylinder deactivation strategy.

PERE and VEHSIM model runs were then generated for a 2004 BMW745i and a 2005 Chrysler 300C and compared to CAFE ratings for these vehicles using actual test weights and engine displacement.

For the PERE runs, road load was represented using the track road load at 50 mph for these vehicles obtained from the EPA I/M lookup table. These engine technologies were modeled in PERE using target coefficients specified in the PERE documentation of a 10% improvement in indicated engine efficiency (from 0.40 to 0.44) and engine friction equivalent to 2015, based on trends developed by EPA.

Based on available literature, Sierra has developed separate VVLT and Cylinder Deactivation engine maps by modifying "existing technology" maps used in VEHSIM. These VVLT and CDEACT maps do not represent uniformly applied reductions in fuel consumption from efficiency gains or reduced friction as applied in PERE, but rather target reductions over selected ranges of the maps. (For example, as stated earlier, cylinder deactivation improves efficiency only at light loads.)

Table 5-5 compares published CAFE ratings for the City and Highway cycles to PERE and VEHSIM model simulations for a 2004 BMW745i and a 2005 Chrysler 300C, containing advanced VVLT and CDEACT technologies, respectively. Relative differences (as a percentage of reported CAFE fuel economy) are also shown in Table 5-5 for each model.

**Table 5-5**
**CAFE vs. Modeled Fuel Economy for**
**Advanced IC Technology Vehicles**

| Vehicle (Technology) | Source | Fuel Economy (mpg) City | Fuel Economy (mpg) Highway |
|---|---|---|---|
| 2004 BMW 745i (VVLT) | Reported CAFE | 20.00 | 33.50 |
| | PERE | 19.62 | 31.91 |
| | VEHSIM | 19.82 | 32.65 |
| | %Diff – PERE | **-1.9%** | **-4.7%** |
| | %Diff - VEHSIM | **-0.9%** | **-2.6%** |
| 2005 Chrysler 300C (CDEACT) | Reported CAFE | 18.80 | 31.50 |
| | PERE | 17.10 | 26.73 |
| | VEHSIM | 18.67 | 31.12 |
| | %Diff – PERE | **-9.1%** | **-15.1%** |
| | %Diff - VEHSIM | **-0.7%** | **-1.2%** |

As shown in Table 5-5, although the PERE model fuel economy is in good agreement with reported CAFE for the VVLT simulation of a 2004 BMW745i, it severely underpredicts CAFE fuel economy for the CDEACT simulation of a 2005 Chrysler 300C. This has nothing to do with the fact that PERE does not treat cold starts since Highway fuel economy (a test run warmed up) and the error on the Highway cycle is greater than the error on the City cycle. For both technologies and cycles, VESHIM matches the CAFE results for both these advanced technology vehicles very closely to within 0.7% to 2.6%.

To more clearly examine the impacts of PERE's use of a uniform change in indicated efficiency (and friction) to "generically" model all types of advanced IC technologies, the same two vehicles described above were also modeled with existing IC engine assumptions. For PERE, this consisted of using the existing fleet "baseline" values of indicated engine efficiency and engine friction. For VEHSIM, the conventional spark-ignition engine maps from which the VVLT and CDEACT maps were developed were used.

VEHSIM also includes the ability to dynamically resize an engine to match 0-30 mph or 0-60 mph performance of a baseline or reference case. Since VVLT engines have greater power density (power per unit displacement) than conventional engines, a new VVLT-equipped vehicle does not have to be designed with the same engine size and the model it is replacing and can be "downsized" to match performance characteristics (such as 0-30 or 0-60 times) of the conventional engine. Thus, the VEHSIM VVLT simulations were performed two ways: (1) with the same engine; and (2) with a resized engine that matched 0-30 and 0-60 performance of the conventional engine. The PERE model cannot resize an engine to match "baseline" performance. All other input parameters were kept the same between existing and advanced technology simulations for each vehicle.

Table 5-6 presents the results of this comparison. It shows that over a range of cycles that include varying degrees of light load/mild operation versus higher load/aggressive operation, the PERE model shows nearly identical relative improvements in fuel economy for advanced technologies over existing IC engines. For both the VVLT and CDEACT scenarios shown in Table 5-6, PERE's relative improvements range tightly between 11.0% and 13.0%. (PERE's relative improvements are not exactly identical because of frictional gains modeled for advanced technologies that are greater at lower speeds.)

On the other hand, the relative fuel economy improvements for these technologies modeled by VEHSIM are significantly lower for cycles with less operation in regions of the engine map where these technologies actually improve fuel efficiency. For example, relative improvements from cylinder deactivation modeled with VEHSIM on the LOS A cycle (7.5%) are only half of those modeled for the Hot-City cycle (14.9%). This reduction is expected since the LOSA cycle contains much less light load operation than the City cycle where cylinder deactivation improves fuel efficiency.

| Table 5-6<br>Modeled Fuel Economy Improvement of Advanced IC Technology Vehicles | | | | | | |
|---|---|---|---|---|---|---|
| Technology (Vehicle) | Model | | Fuel Economy (mpg) | | | |
| | | | City-Hot | Highway | UC | LOSA |
| **VVLT** (BMW745i) | PERE | Existing IC | 17.36 | 28.46 | 17.29 | 23.89 |
| | | Adv –VVLT (No Resize) | 19.62 | 31.91 | 19.44 | 26.61 |
| | | **%Change** | **13.0%** | **12.1%** | **12.4%** | **11.4%** |
| | VEHSIM | Existing IC | 18.35 | 29.57 | 18.23 | 25.43 |
| | | Adv –VVLT (No Resize) | 20.33 | 32.65 | 19.76 | 26.97 |
| | | Adv –VVLT (Resize) | 21.61 | 34.19 | 20.53 | 27.63 |
| | | **%Change (No Resize)** | **10.8%** | **10.4%** | **8.4%** | **6.0%** |
| | | **% Change (Resize)** | **17.8%** | **15.6%** | **12.6%** | **8.7%** |
| **CDEACT** (Chry 300C) | PERE | Existing IC | 15.20 | 23.94 | 15.53 | 20.16 |
| | | Adv - CDEACT | 17.10 | 26.73 | 17.40 | 22.38 |
| | | **%Change** | **12.5%** | **11.6%** | **12.0%** | **11.0%** |
| | VEHSIM | Existing IC | 16.67 | 27.28 | 17.16 | 24.23 |
| | | Adv - CDEACT | 19.15 | 31.12 | 18.87 | 26.05 |
| | | **%Change** | **14.9%** | **14.1%** | **9.9%** | **7.5%** |

The comparisons in Table 5-6 clearly reveal the flawed and highly simplistic treatment of advanced IC technologies in the PERE model. Since estimates of future fleet vehicle energy consumption in MOVES are based on this simplistic "linear efficiency" treatment of all types of advanced IC engines, its ability to project forward is also fatally flawed.

Hybrid Technologies – In addition to the advanced IC technologies, hybrid technologies were evaluated. Table 5-7 compares modeled to reported CAFE fuel economy for the 2003 Toyota Prius, which EPA terms a "full" hybrid.

| Table 5-7<br>CAFE vs. Modeled Fuel Economy for<br>Full Hybrid Technology Vehicles | | | | | |
|---|---|---|---|---|---|
| Vehicle (Technology) | Source | Fuel Economy (mpg) | | | |
| | | City | Highway | UC | LOSA |
| 2003 Toyota Prius (Advanced Hybrid) | Reported CAFE | 66.60 | 64.80 | n/a | n/a |
| | PERE | 52.63 | 64.69 | 42.48 | 53.12 |
| | VEHSIM | 63.91 | 64.07 | 53.22 | 42.35 |
| | %Diff – PERE | **-21.0%** | **-0.2%** | n/a | n/a |
| | %Diff - VEHSIM | **-4.0%** | **-1.1%** | n/a | n/a |

The PERE estimates shown in Table 5-7 were developed using guidance for modeling engine friction, battery and motor characteristics of full hybrids in Appendix B of EPA's February 2005 PERE report.[6] As stated earlier, EPA's proposed approach to modeling a "full hybrid" vehicle like the Prius fails to account for the available battery power being substantially less than the available electric motor power. To use the full rated power of the electric motors, it is necessary to run the combustion engine and spin the generator. Conversely, VEHSIM uses an algorithm to account for the energy supplied by an advanced regenerative braking system based on the instantaneous power absorption rate, energy conversion efficiency, and battery and motor capacities reported for the Prius that account for the battery power being less than that available from the electric motor.

The PERE model poorly predicts hybrid fuel economy over the City cycle, as shown in Table 5-7. The differences in modeled results in Table 5-7 for the UC and LOS A cycles also reveal the problems with the treatment of hybrids in PERE. Like the City cycle, the UC contains a significant amount of low/moderate speed stop-and-go driving. In contrast, the LOSA cycle contains sustained high-speed operation (with an average speed of 67.8 mph) where the benefits of regenerative braking are diminished and the IC engine in the Prius is less fuel efficient. VEHSIM correctly simulates poorer hybrid fuel economy on the LOSA cycle than the UC cycle. PERE incorrectly has it backwards.

## 5.4 Potential to Model Criteria Pollutants

As discussed above, the PERE model can estimate carbon dioxide emissions based on empirical relationships between engine load and fuel efficiency. For conventional gasoline engines, there are reasonably consistent relationships between fuel consumption and power output; however, in the case of criteria pollutants, there are many other factors that affect vehicle emissions. These factors include air-fuel ratio, spark timing, and catalytic converter efficiency.

Nothing in the available documentation of the PERE model provides any indication of how EPA proposes to use the model to address criteria pollutants. However, it is clear that there is no apparent relationship between fuel consumption and the emissions of HC, CO, and NOx emissions from either individual vehicles or major segments of the vehicle fleet on the Federal Test Procedure. For over 30 years, passenger cars and light-duty trucks have been required to meet mass emissions standards that are independent of the amount of fuel burned by the vehicle. In addition, the stringency of the emissions standards changed dramatically during a period of time when fuel consumption for cars and light trucks remained relatively constant. To the extent that some relationship exists between engine-out emissions and power demand, it has been, and will continue to be, necessary for vehicle manufacturers to add additional aftertreatment capability, or other emissions controls, to overcome the tendency toward higher emissions that is associated with vehicles requiring more power to drive the emissions testing cycle. As a result, there is no correlation that can be established between fuel consumption and criteria pollutant emissions when individual vehicles are compared to one another.

Notwithstanding the lack of correlation described above, there may be some correlation between fuel consumption and criteria pollutant emissions when an individual vehicle is compared to itself using two different driving cycles. Cycles requiring higher engine loads will result in reduced exhaust residence time in the catalytic converter and higher volumetric flow rates of exhaust. Both of these factors would be expected to contribute to higher exhaust emissions. But, due to the complexities involved, the accuracy of criteria pollutant estimates based on changes in fuel consumption can be expected to be less than the accuracy with which the model predicts changes in carbon dioxide. The relationship between catalyst efficiency exhaust flow rate will depend on the size of the catalysts being used. Nevertheless, some crude approach to estimating emissions on undriven cycles might be developed based on adjusting emissions results from other cycles by the estimated change in fuel consumption rate and catalyst space velocity.

Notwithstanding the theoretical considerations discussed above, it is not clear how EPA could go about developing a model that would accurately estimate the emissions of untested combinations of technologies and driving cycles. Once warmed up, vehicles designed to meet the Tier 2 or LEV II standards have near-zero emissions on the Federal Test Procedure. They can be expected to maintain near-zero emissions under driving cycles that provide equivalent or greater residence time for exhaust gas in the catalytic converters. The biggest unknown is the extent to which such vehicles will experience emissions-related defects in customer service and how those defects will end up affecting emissions on various types of driving cycles.

In previous modeling efforts, emissions have been projected based on the assumption that an increasing percentage of vehicles would be at multiples of the standards as mileage is accumulated. However, the fraction of vehicles that will exceed the standards at various mileages, and the amount by which the standards will be exceeded, is unlikely to be the same for Tier 2 and LEV II vehicles as it has been historically. Improved fuel quality and increased vehicle reliability and durability have reduced the fraction of the vehicles that will exceed certification standards at any particular mileage. However, should defects occur that are uncorrected, emissions may increase to a higher multiple of the standards because the standards are so much closer to zero and the effect of certain types of defects will be similar on a g/mi basis. (For example, a fail-lean mode will cause the catalyst to lose NOx efficiency and the vehicle will emit engine-out NOx emissions similar to those of older vehicles. The increase in g/mi of NOx will be higher on a percentage basis.)

In summary, we have serious concerns about the ability of PERE to model criteria pollutant emissions for the following reasons:

- The use of aftertreatment devices to control criteria pollutant emissions to varying degrees as a function of power demand is very vehicle-specific, and automotive engineers spend a significant amount of time calibrating <u>each engine family</u> for optimum emissions performance. As a result, it is impossible to develop a single relationship relating emissions to power demand as was done in the current version of PERE for estimating fuel consumption as a function of power demand.

- Modeling of $CO_2$ emissions with a physical model such as PERE is much more straightforward than modeling criteria pollutant emissions. If an attempt is made to revise PERE to model criteria pollutants, significant uncertainty will be introduced.

Given the above, it is doubtful that using a revised version of PERE, or a model based on PERE, to estimate criteria pollutant emissions of future technology vehicles will be any more accurate than the historical method of scaling emission rates of current technology vehicles (for which data are available) by the ratio of future-to-current emissions standards.

## 5.5 Review of Alliance Comments

EPA's overall response to previous Alliance comments on the PERE model was summarized by EPA as follows:

> *The PERE model will NOT be used in MOVES to capture the behavior of a specific vehicle, but rather a fleet of vehicles. Therefore, the accurate representation of its components (transmission, motor, etc) was not the goal.*

This summary and EPA's detailed response to specific comments by the Alliance indicates that the agency failed to recognize the significance of many of the comments. Since PERE is intended to fill data gaps, it will most often be required to estimate emissions from vehicles that are not yet built and tested. Since light-duty vehicles are continually evolving, it is important for the model to be able to accurately account for the changes in vehicle design that are occurring. The automotive industry is investing billions of dollars in the development of engine and transmission technologies that provide greater levels of fuel efficiency. The fact that PERE is intended to represent the emissions of the fleet rather than individual vehicles does not mean that "the accurate representation" of engines and transmissions is unimportant. In fact, the accurate representation of evolving technology should be the goal.

In responding to detailed comments, EPA sometimes acknowledges a limitation of the model that has been identified by the Alliance, but more often is dismissive of important points raised by the Alliance.

An example of an EPA response that fails to recognize the significance of Alliance comments is the response to the comment that the validation effort did not address different types of transmissions. EPA responded by saying the following:

> *Since the engine model is based on power (and not torque), transmission takes on secondary importance.*

This response indicates that EPA completely failed to understand the point being made in the comment from the Alliance. Transmissions have a significant effect on the fuel economy and carbon dioxide emissions emitted by a vehicle. Rather than acknowledging the PERE is incapable of accounting for transmission differences, EPA responds with a statement about transmissions being of "secondary importance" because "the engine model is based on power (and not torque)." The implication is that the form of the model somehow affects the actual importance of the transmission. In reality, the form of the model makes it incapable of properly accounting for differences in transmissions. Given the substantial changes in transmission design being introduced into the fleet, this limitation of the model directly affects its ability to accurately represent the future fleet.

Similarly, when the Alliance made the comment that the fuel economy benefits of advanced technologies "depend on the drive cycle" and that "the ability to use PERE to estimate corresponding FE benefits on unspecified customer cycles has not been demonstrated," EPA's response was the following:

> *The hope is that at the level MOVES models energy rates, the fuel rates by operating mode bin (VSP) will be relatively independent of (most) drive cycles effects.*

As was the case with EPA's response to the Alliance's concerns about the inability of PERE to account for transmission differences, the agency did not seem to take the concern about drive cycle dependence seriously. "Hoping" that the fuel economy benefits of advanced technologies will be independent of drive cycle effects indicates a failure of the agency to understand the non-uniform way in which many advanced technologies affect fuel economy over the full range of vehicle operation in customer service. As discussed above, increasingly popular technologies like cylinder deactivation systems have fundamentally different effects on fuel economy during low speed, stop-and-go driving than they do during higher speed, higher load operation. A model that doesn't account for such differences can't possibly be expected to accurately represent the effect of changes in driving patterns on vehicle emissions.

In response to the Alliance comment that differences in pumping losses are not significant between 2-valve and 4-valve engines, EPA responded as follows:

> *The friction term (fmep) includes the improvement in "breathing" that accompanies the increase in area of the intake (and exhaust) openings.*

Again, EPA's response indicates that it fails to understand the point the Alliance was making, and that it is treating in a dismissive manner. Pumping loss is most significant at light engine loads where the throttle is nearly closed and the engine must work against the high intake manifold vacuum as the fresh charge is drawn into the chamber. Under these conditions, valve area of a 2-valve engine is not a constraint and the larger valve area of a 4-valve engine has no effect on the level of intake manifold vacuum associated with the power level the engine is producing. EPA's response indicates that it fails to understand this critical fact.

With respect to the Alliance comment about the PERE model not being validated for a wide range of vehicles and driving cycles, EPA responded as follows:

> *The PERE model has been validated against 41 "conventional" passenger vehicles driven on the FTP as well as US06 cycles in a previously published report: (Nam, EPA document number: 420-R-03-005, Table 2). In the same document, analyses were conducted against another 17 vehicles driven on a series of 8 cycles developed by CARB (UCC cycles). Moreover, the same modeling methodology has been proven robust by a number of researchers in several different (peer-reviewed) publications.*

However, as discussed above, the simplistic manner in which PERE treats advanced technologies leads to large errors for certain driving cycles. Rather than recognize such limitations of the model, EPA focuses on what has been shown for selected vehicles and selected driving cycles.

Perhaps the most telling response to Alliance comments is found in EPA's explanation of why more sophisticated vehicle simulation models like ADVISOR have not been used. EPA's response was as follows:

> *PERE has been validated to the [sic] some of the same vehicles that ADVISOR has been validated with.*

This response makes it appear as though EPA is committed to the use of a simplistic and fundamentally flawed model and fails to understand that the claimed "validation" is inadequate, especially for advanced technologies.

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# 6. REVIEW OF MOVES2004 VEHICLE FLEET AND ACTIVITY INPUT DATA

This section presents a review of the fleet and activity data used in the MOVES model. One key element new to the MOVES model is that it includes national vehicle activity data resolved to the county level and reports total on-highway emissions and fuel economy. MOBILE6.2, in contrast, only estimates factors reported as emissions per unit of activity (e.g., grams per mile), and activity data has always been maintained separately from the MOBILE series of models. Another key element of the MOVES model is the resolution of rates by operating mode or VSP bin (fuel consumption rates and emission rates in future versions). This review focuses on the elements new to the MOVES model and in particular the methodology used to estimate the proportion of travel time by the VSP operating bins.

The fleet and activity inputs used in MOVES2004 are described in the December 2004 EPA draft report, "MOVES2004 Highway Vehicle Population and Activity Data."[7] The fleet data in the report include vehicle population estimates, age distributions, survival rates, sales growth rates, and the distribution of vehicles across source bins. Activity data include vehicle miles traveled (VMT), VMT growth, average speed distributions, and driving patterns.

This review addresses the following topics:

- National Default Databases
- County Allocation
- VSP Binning Methodology
- Discussion and Issues of Concern

## 6.1 Summary of MOVES2004 Activity Estimates

National Default Databases – In populating the MOVES2004 default activity databases, EPA relied on a number of data sources, many of which were developed outside the agency. Most data were compiled for or relative to the 1999 calendar year. 1999 is considered the base calendar year for the MOVES2004 model, and years after 1999 are considered projection years. The following are summaries of the key sources of national default data that are used in MOVES2004.

- VIUS – Every fifth year, the U.S. Census Bureau conducts the Vehicle Inventory and Use Survey (VIUS) to collect fleet and activity data for trucks operating in the U.S. EPA relied on the 1997 VIUS to provide information to characterize trucks by source type and to estimate truck age distributions.

- R.L. Polk & Company – R.L. Polk is a private company that maintains databases on vehicle registrations. EPA used 1999 versions of Polk databases to provide state vehicle registration data for light-duty cars and trucks as well as medium- and heavy-duty trucks.

- FHWA Highway Statistics – EPA used the annual Federal Highway Administration's (FHWA) publication *Highway Statistics* for VMT and registration data. Base year (1999) data for registrations and VMT came from the 1999 publication. 2000 through 2002 publications were used to develop VMT projections for each of those years.

- AEO – Data from the Department of Energy's (DOE) *2004 Annual Energy Outlook* (AEO) and supporting National Energy Modeling System (NEMS) were used to provide forecasted VMT growth and vehicle sales growth for 2004 and beyond.

- Transportation Energy Data Book – EPA relied on 2002 and 2003 versions of the annual publication *Transportation Energy Data Book* published by Oak Ridge National Laboratory to determine weight distributions for light trucks by model year.

- MOBILE6 – EPA incorporated MOBILE6 modeling assumptions into MOVES to address specific fleet and activity inputs. Included in these are vehicle starts per day, vehicle speed distributions (urban areas only),[*] air conditioning penetration rates, and relative mileage accumulation rates by age.

These sources were used to develop the default databases incorporated into MOVES2004 for vehicle population estimates, VMT, VMT growth, speed distributions, age distributions, survival rates, sales growth rates, and the distribution of vehicles across source bins. The default data represent national average conditions. The model allows for the substitution of user-supplied fleet and activity data. In this release of the model, EPA has not released any guidelines outlining how to develop local-specific modeling data. The agency has indicated that future releases of MOVES will include guidance on when inputs should be modified and when modeling defaults should be retained.

[*] MOBILE6 speed distribution data were considered representative of urban areas. For rural areas, EPA relied on speed distributions developed by Sierra Research based on chase car studies performed in California.

Allocation of National Activity Data to Counties – MOVES2004 distributes national VMT and vehicle starts down to the county level for use in county-level or state-level analyses. The estimates for the allocation of VMT by county come from the 1999 National Emission Inventory (NEI) analysis prepared by Pechan & Associates.[8] The NEI estimates are based on the Highway Performance Monitoring System (HPMS) data collected by the FHWA and are also those used in EPA's National Mobile Inventory Model (NMIM) county database. VMT data are distinguished by the 12 HPMS roadway classifications shown in Table 6-1.

| **Table 6-1**<br>**12 HPMS Roadway Classifications Used in MOVES** |
|---|
| Rural Interstate |
| Rural Principal Arterial |
| Rural Minor Arterial |
| Rural Major Collector |
| Rural Minor Collector |
| Rural Local |
| Urban Interstate |
| Urban Freeway/Expressway |
| Urban Principal Arterial |
| Urban Minor Arterial |
| Urban Collector |
| Urban Local |

National VMT by HPMS roadway type is allocated based on the fraction of national VMT for that roadway type that is estimated to be in each county. As a result, in MOVES2004 the county allocation values for each roadway type sum to one for the nation. The allocation data represent the 1999 calendar year estimates and the model uses the 1999 allocations for all calendar years. The VMT data are also used to allocate vehicle starts to the county level. In allocating vehicle starts, the county VMT allocation factors are not resolved by roadway type. Rather, total VMT across all 12 HPMS roadway classifications is used. Given this approach to VMT allocation, MOVES2004 in fact relies on county-specific estimates for the proportion of travel by roadway classification. These VMT data are the only fleet and activity data that are geographic specific. The remaining fleet and activity data of the model represent national conditions.

VSP Binning Methodology – In order for MOVES to estimate modal fuel consumption by operating mode bin (defined by VSP level), the model must estimate the proportion of vehicle travel time in each of the VSP operating mode bins. In MOVES, total activity is defined by source hours of operation (SHO) and the model apportions SHO into the VSP bins according to the following methodology.

The model relies on the VSP bin distribution of the 40 driving cycles included in MOVES2004 by EPA and then apportions estimated travel time to the driving cycles based on assumed speed distributions by vehicle type, roadway type and the distribution of travel by roadway type. The VSP bins for the driving cycles are estimated from the time trace of the driving cycle and the VSP equation coefficients of a given source type (e.g., passenger cars). In this manner, the modal activity of MOVES is based on the modal activity of specific driving cycles and the estimated proportion of time spent in those cycles.

For light-duty vehicle operation, MOVES defines 14 driving cycles shown in Table 6-2. The average speed of these cycles ranges from 2.5 mph to 76.0 mph. The model has a total of 40 driving cycles, and the remaining 26 characterize the operation of heavy-duty vehicle source types. Ten of the 14 light-duty driving cycles used in MOVES2004 were developed for use in vehicle testing programs that generated the data upon which the speed correction factors in MOBILE6 are based. The two exceptions are the High Speed Freeway 2 and High Speed Freeway 3 cycles developed for MOVES[*] and the Low Speed 1 and New York City cycles, which predate the MOBILE6 model. The estimated VSP bin distributions for automobiles operating on the light-duty driving cycles are shown in Table 6-3.[†]

**Table 6-2. Light-Duty (LD) Driving Cycles**

| Driving Cycle | Average Speed (mph) |
|---|---|
| LD Low Speed 1 | 2.5 |
| LD New York City | 7.1 |
| LD LOS EF Non-Freeway | 11.6 |
| LD LOS CD Non-Freeway | 19.2 |
| LD LOS AB Non-Freeway | 24.8 |
| LD LOS G Freeway | 13.1 |
| LD LOS F Freeway | 18.6 |
| LD LOS E Freeway | 30.5 |
| LD LOS D Freeway | 52.9 |
| LD LOS AC Freeway | 59.7 |
| LD High Speed Freeway 1 | 63.2 |
| LD High Speed Freeway 2 | 68.2 |
| LD High Speed Freeway 3 | 76.0 |
| LD Freeway Ramp | 34.6 |

[*] High Speed 2 and 3 were developed by EPA to address the concern that the MOBILE6 driving cycles did not adequately capture the range of high speed freeway driving in-use due in part due to recent increases in speed limits as well as vehicle performance improvements. High Speed 2 is a 240-second segment of the US06 certification compliance cycle, with an average speed of 68 mph and a maximum of 80 mph. High Speed 3 is 580-second segment of freeway driving from an in-use vehicle instrumented as part of EPA's On-Board Emission Measurement "Shootout" program.
[†] The data of Table 6.3 are specific to automobiles. The values for light-duty trucks are similar but different as the VSP equation coefficients are distinct for these two light-duty vehicle classes.

**Table 6.3. Fraction of Driving Cycle Travel Time by Operating Mode Bin (or VSP Bin), MOVES Default Automobiles**

| | Operating Mode Bin (or VSP Bin) | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Driving Cycle | Bin 0 | Bin 1 | Bin 11 | Bin 12 | Bin 13 | Bin 14 | Bin 15 | Bin 16 | Bin 21 | Bin 22 | Bin 23 | Bin 24 | Bin 25 | Bin 26 | Bin 33 | Bin 35 | Bin 36 |
| LD Low Speed 1 | 1.5% | 50.2% | 15.3% | 32.6% | 0.3% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| LD New York City | 10.5% | 42.3% | 13.1% | 17.6% | 7.8% | 2.5% | 2.2% | 1.7% | 0.2% | 0.5% | 1.2% | 0.2% | 0.2% | 0.2% | 0.0% | 0.0% | 0.0% |
| LD LOS EF Non-Freeway | 12.9% | 33.8% | 7.6% | 13.5% | 6.2% | 3.4% | 2.2% | 2.0% | 4.4% | 1.8% | 4.4% | 2.4% | 2.8% | 2.8% | 0.0% | 0.0% | 0.0% |
| LD LOS CD Non-Freeway | 13.9% | 22.5% | 7.2% | 7.2% | 3.8% | 4.6% | 1.6% | 2.4% | 7.6% | 7.8% | 5.3% | 5.6% | 4.9% | 5.7% | 0.0% | 0.0% | 0.0% |
| LD LOS AB Non-Freeway | 12.8% | 15.1% | 3.9% | 5.4% | 4.1% | 2.9% | 1.9% | 2.4% | 9.0% | 7.1% | 10.7% | 7.7% | 3.9% | 5.0% | 2.6% | 3.1% | 2.3% |
| LD LOS G Freeway | 8.2% | 4.4% | 29.0% | 33.2% | 11.3% | 4.6% | 1.0% | 0.5% | 0.5% | 0.8% | 2.1% | 2.1% | 1.5% | 0.8% | 0.0% | 0.0% | 0.0% |
| LD LOS F Freeway | 12.2% | 3.6% | 16.3% | 23.1% | 10.4% | 4.1% | 1.6% | 2.0% | 4.1% | 5.4% | 4.3% | 3.9% | 3.4% | 5.4% | 0.0% | 0.0% | 0.0% |
| LD LOS E Freeway | 11.4% | 1.8% | 8.6% | 9.5% | 7.5% | 2.6% | 3.7% | 0.7% | 7.3% | 10.5% | 5.3% | 5.5% | 3.7% | 5.5% | 4.8% | 5.5% | 6.2% |
| LD LOS D Freeway | 4.2% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 5.4% | 5.2% | 4.9% | 4.7% | 3.7% | 6.2% | 19.0% | 18.5% | 28.1% |
| LD LOS AC Freeway | 1.4% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.4% | 0.6% | 0.8% | 0.2% | 0.6% | 1.2% | 25.6% | 29.7% | 39.6% |
| LD High Speed Freeway 1 | 2.1% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 20.7% | 29.9% | 47.3% |
| LD High Speed Freeway 2 | 3.3% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 10.8% | 23.8% | 62.1% |
| LD High Speed Freeway 3 | 0.9% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 9.0% | 14.7% | 75.5% |
| LD Freeway Ramp | 10.6% | 6.4% | 4.9% | 4.5% | 3.0% | 1.9% | 2.3% | 0.4% | 9.1% | 4.2% | 4.5% | 3.8% | 4.2% | 19.6% | 9.1% | 3.4% | 8.3% |

The proportion of travel time by the driving cycles shown in Table 6-3 is then determined from the proportion of travel by roadway and the assumed speed distributions by roadway. Table 6-4 presents the proportion of VMT for the 12 HPMS roadway types modeled in MOVES. These data, representing national average automobile travel, are converted to a fraction of time spent by roadway by dividing by the roadway average speed. According to the default national average data, 26.1 and 73.9 percent of automobile SHO is spent on rural and urban roadways, respectively, and 21.0 percent of SHO occurs on interstates and freeways (rural and urban combined).

**Table 6-4**
**Travel Distribution by Roadway**
**MOVES Default, Automobiles**

| Roadway Type | VMT Fraction (%) | Time Fraction (%) |
|---|---|---|
| Rural Interstate | 8.3 | 3.8 |
| Rural Principal Arterial | 8.7 | 4.8 |
| Rural Minor Arterial | 6.0 | 4.1 |
| Rural Major Collector | 7.5 | 6.2 |
| Rural Minor Collector | 2.1 | 1.9 |
| Rural Local | 4.5 | 5.4 |
| Urban Interstate | 14.3 | 11.8 |
| Urban Freeway/Expressway | 6.7 | 5.5 |
| Urban Principal Arterial | 15.3 | 15.5 |
| Urban Minor Arterial | 12.2 | 12.4 |
| Urban Collector | 5.1 | 5.2 |
| Urban Local | 9.1 | 23.6 |
| ***Total Rural*** | **37.2** | **26.1** |
| ***Total Urban*** | **62.8** | **73.9** |

The speed distribution data of MOVES is divided into 16 speed bins. Fourteen bins are defined by 5 mph ranges starting with 2.5 mph to 72.5 mph, and two additional bins account for travel below 2.5 mph and travel above 72.5 mph. For example, one speed bin encompasses travel between 52.5 mph and 57.5 mph with an assumed average speed of 55.0 mph. The speed distribution data of MOVES are defined as the fraction of SHO by roadway by speed bin. SHO by speed bin are then apportioned to the two driving cycles which bracket the average speed of the bin. Travel at 55 mph is bracketed by the LOS D Freeway cycle (average speed of 52.9 mph) and LOS AC Freeway cycle (average speed of 59.7 mph). Travel in the 55 mph speed bin is then assigned to 69.1 percent LOS D Freeway and 30.9 percent LOS AC Freeway where the weight factors are determined such that the combined cycle average speed matches that of the speed bin (55 mph). Following this technique, the speed distribution data by roadway are converted to the distribution of time spent in each driving cycle. The results of this calculation for national average automobile operation are shown in Table 6-5.

**Table 6.5. Fraction of Travel Time by Driving Cycle - MOVES Default Speed Distributions, Automobiles**

| | Driving Cycle | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Roadway** | LD Low Speed 1 | LD New York City | LD LOS EF Non-Freeway | LD LOS CD Non-Freeway | LD LOS AB Non-Freeway | LD LOS G Freeway | LD LOS F Freeway | LD LOS E Freeway | LD LOS D Freeway | LD LOS AC Freeway | LD High Speed Freeway 1 | LD High Speed Freeway 2 | LD High Speed Freeway 3 | LD Freeway Ramp |
| Rural Interstate | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.8% | 4.5% | 11.6% | 33.6% | 41.6% | 8.0% |
| Rural Principal Arterial | 0.3% | 0.7% | 0.6% | 0.9% | 0.8% | 0.0% | 0.0% | 9.4% | 24.6% | 20.7% | 13.4% | 19.9% | 8.7% | 0.0% |
| Rural Minor Arterial | 0.4% | 0.3% | 0.7% | 2.0% | 4.7% | 0.0% | 0.0% | 23.6% | 39.6% | 18.3% | 5.1% | 3.8% | 1.2% | 0.0% |
| Rural Major Collector | 0.4% | 0.8% | 1.6% | 7.6% | 5.9% | 0.0% | 0.0% | 38.0% | 42.8% | 2.7% | 0.1% | 0.0% | 0.0% | 0.0% |
| Rural Minor Collector | 0.0% | 0.3% | 3.9% | 8.9% | 10.5% | 0.0% | 0.0% | 43.3% | 31.0% | 2.1% | 0.0% | 0.0% | 0.0% | 0.0% |
| Rural Local | 3.0% | 5.6% | 18.3% | 24.8% | 9.4% | 0.0% | 0.0% | 16.5% | 18.4% | 3.5% | 0.2% | 0.0% | 0.0% | 0.0% |
| Urban Interstate | 18.4% | 3.3% | 1.1% | 0.0% | 0.0% | 0.8% | 2.9% | 11.9% | 23.9% | 26.6% | 2.9% | 0.4% | 0.0% | 8.0% |
| Urban Freeway/Expressway | 18.4% | 3.3% | 1.1% | 0.0% | 0.0% | 0.8% | 2.9% | 11.9% | 23.9% | 26.6% | 2.9% | 0.4% | 0.0% | 8.0% |
| Urban Principal Arterial | 5.5% | 1.4% | 1.3% | 4.8% | 14.9% | 0.0% | 0.0% | 52.0% | 18.9% | 1.1% | 0.1% | 0.0% | 0.0% | 0.0% |
| Urban Minor Arterial | 5.5% | 1.4% | 1.3% | 4.8% | 14.9% | 0.0% | 0.0% | 52.0% | 18.9% | 1.1% | 0.1% | 0.0% | 0.0% | 0.0% |
| Urban Collector | 5.5% | 1.4% | 1.3% | 4.8% | 14.9% | 0.0% | 0.0% | 52.0% | 18.9% | 1.1% | 0.1% | 0.0% | 0.0% | 0.0% |
| Urban Local | 0.0% | 18.6% | 60.1% | 21.3% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| ***Rural Average*** | ***0.8%*** | ***1.6%*** | ***4.7%*** | ***8.0%*** | ***5.0%*** | ***0.0%*** | ***0.0%*** | ***20.9%*** | ***26.9%*** | ***8.8%*** | ***5.0%*** | ***9.1%*** | ***7.8%*** | ***1.2%*** |
| ***Urban Average*** | ***6.8%*** | ***7.3%*** | ***20.0%*** | ***8.9%*** | ***6.6%*** | ***0.2%*** | ***0.7%*** | ***26.0%*** | ***14.0%*** | ***6.7%*** | ***0.7%*** | ***0.1%*** | ***0.0%*** | ***1.9%*** |
| ***Overall Average*** | ***5.2%*** | ***5.8%*** | ***16.0%*** | ***8.7%*** | ***6.2%*** | ***0.1%*** | ***0.5%*** | ***24.7%*** | ***17.4%*** | ***7.3%*** | ***1.9%*** | ***2.4%*** | ***2.0%*** | ***1.7%*** |

MOVES combines the fraction of operation time by driving cycle (Table 6-5) with the VSP bin distribution by driving cycle (Table 6-3) to estimate the overall VSP bin distribution for the modeling scenario. The results for national average automobiles are shown in Table 6-6.

Of the results shown in Table 6-6, of interest is the proportion of time spent at the high speed bins (bins 33, 35, and 36 defined for vehicle operation at or above 50 mph) and the proportion of travel time at high VSP bins (bins 26 and 36 with VSP at or greater than 12 kW/tonne) where fuel consumption rates (and emission rates, as discussed in Section 4) are relatively higher. A significant portion of travel is occurring at the high speed bins (33, 35 and 36), estimated at 29.5% of the time for automobiles using the default modeling assumptions. Also a significant portion of travel is occurring at the high VSP bins (26 and 36), estimated at 17.7% of the time for automobiles using the default modeling assumptions.

| Table 6-6<br>Fraction of Travel Time (%) by Operating Mode Bin (or VSP Bin)<br>MOVES Default Automobiles | | | |
|---|---|---|---|
| VSP Bin | Rural Average | Urban Average | Overall Average |
| Bin 0 | 6.8 | 9.5 | 8.8 |
| Bin 1 | 5.7 | 16.9 | 13.9 |
| Bin 11 | 3.3 | 6.9 | 6.0 |
| Bin 12 | 4.1 | 10.0 | 8.4 |
| Bin 13 | 2.5 | 4.5 | 4.0 |
| Bin 14 | 1.3 | 2.2 | 2.0 |
| Bin 15 | 1.2 | 1.9 | 1.7 |
| Bin 16 | 0.6 | 1.1 | 1.0 |
| Bin 21 | 4.4 | 5.0 | 4.9 |
| Bin 22 | 4.8 | 5.2 | 5.1 |
| Bin 23 | 3.7 | 4.4 | 4.2 |
| Bin 24 | 3.4 | 3.7 | 3.6 |
| Bin 25 | 2.6 | 2.9 | 2.8 |
| Bin 26 | 4.0 | 4.2 | 4.1 |
| Bin 33 | 11.4 | 6.1 | 7.5 |
| Bin 35 | 13.8 | 6.5 | 8.4 |
| Bin 36 | 26.5 | 8.9 | 13.5 |

## 6.2 Critical Review of MOVES2004 Activity Estimates

The findings of our critical review of the MOVES2004 activity data are summarized below.

Data Sources – Based on our review, we believe that EPA is correct in relying on fleet and activity data developed from sources outside the agency. This approach eliminates inconsistencies in data generated by different federal agencies (for example, VMT projections from EPA have not matched those produced by the Department of Energy in the past). In addition, because many key MOVES2004 data sources are annual government publications, the underlying data can and should be updated regularly as new data become available. Also, National Energy Modeling System (NEMS) based VMT projections used in support of the Annual Energy Outlook represent a more robust source of VMT projections than prior methods used by EPA.

Allocation of VMT and Starts – The county allocation of VMT by roadway class in MOVES2004 is a reasonable approach. However, in allocating vehicle starts to the county level using VMT, we do not believe it is reasonable to use interstate and freeway VMT because vehicle starts are not generally occurring on these roadways. The current method as applied to starts will overstate the number of starts in remote rural areas that have a freeway passing through but do not have a significant amount of non-freeway activity.

Cycle Representativeness – Most of the 14 light-duty driving cycles used in MOVES2004 were developed based on actual in-use driving and should be suitable for use with the MOVES modeling approach. However, we believe that some of the cycles included in MOVES2004 are questionable with respect to their being representative of actual in-use driving.

The lowest two speed cycles currently contained in the model (Low Speed 1 and the New York City Cycle) are of concern because they were not developed using a technique that ensures they represent actual in-use operation. These cycles were not derived from the same chase car or instrumented data generally used to develop the other facility cycles. Because of this, the distribution of modal activity contained in these two cycles may not be representative of in-use vehicle operation at these average speeds. This is a significant issue because these two cycles are estimated to cover 14.1% of urban and 11.0% of overall travel time for automobiles using the default MOVES data (as shown in Table 6-5).

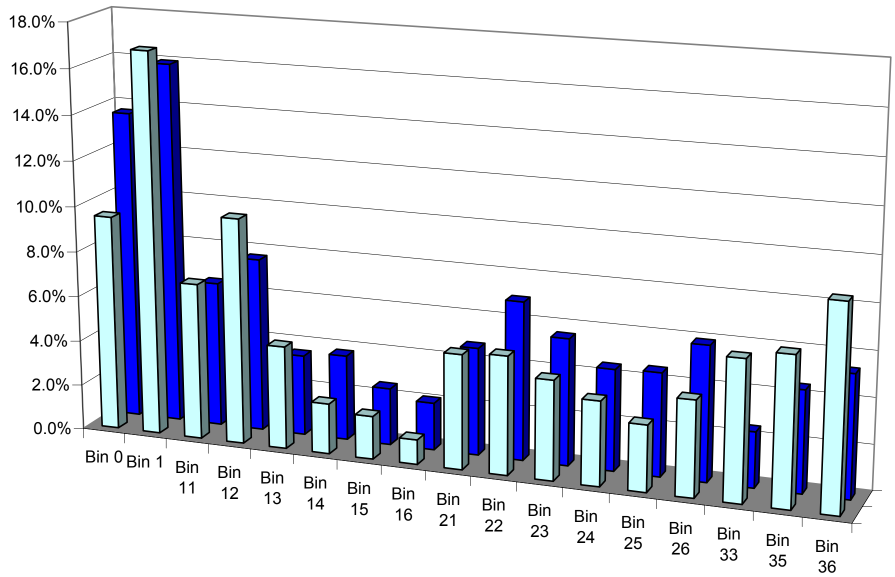
The development of the High Speed 3 cycle for MOVES has not been properly documented by EPA. It is briefly described in the MOVES documentation and appears to have been developed from a single segment of operation by a single instrumented vehicle. If indeed the case, the cycle is unsuitable for inclusion in MOVES2004. Instead, EPA should develop another highest speed cycle using a larger sample of instrumented vehicle data to ensure that it is representative of actual in-use driving. Again, this is a significant issue because this cycle is estimated to cover 7.8% of rural travel time for automobiles using the default MOVES data (as shown in Table 6-5).

VSP Binning – Notwithstanding the issues of cycle representativeness, the general VSP binning approach seems reasonable provided that the activity distribution data by speed and roadway are an accurate reflection of vehicle operation in the modeling domain.

We compared the resulting default MOVES urban VSP bin distribution against another self-weighted urban driving cycle (California ARB's Unified Cycle). The Unified Cycle represents urban operation in the Greater Metropolitan Los Angeles area circa 1992. The results of this comparison are shown in Figure 6.1.

Overall, the VSP bin profiles shown in Figure 6-1 are similar. But differences do exist, which may in part be due to the different activity patterns in Los Angeles versus urban areas nationally. However, one key difference that may not be wholly explained by the differences in regions is the proportion of braking time (bin 0). The Unified Cycle estimates a much greater proportion of braking time – 43% higher than the MOVES urban default.

**Figure 6-1. Percent of Vehicle Operation Time by VSP Bin**
**MOVES Urban Average Versus Unified Cycle, Automobiles**




| | Bin 0 | Bin 1 | Bin 11 | Bin 12 | Bin 13 | Bin 14 | Bin 15 | Bin 16 | Bin 21 | Bin 22 | Bin 23 | Bin 24 | Bin 25 | Bin 26 | Bin 33 | Bin 35 | Bin 36 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MOVES Urban Average | 9.5% | 16.9% | 6.9% | 10.0% | 4.5% | 2.2% | 1.9% | 1.1% | 5.0% | 5.2% | 4.4% | 3.7% | 2.9% | 4.2% | 6.1% | 6.5% | 8.9% |
| Unified Driving Cycle | 13.6% | 15.9% | 6.4% | 7.7% | 3.6% | 3.8% | 2.5% | 2.1% | 4.7% | 7.0% | 5.6% | 4.5% | 4.5% | 5.9% | 2.4% | 4.5% | 5.4% |

<u>Proportion of Activity</u> – As noted earlier, the high speed and high load conditions represent a significant portion of travel. Therefore, the key issue for the accuracy of MOVES is that the supporting fuel consumption rate data (and emission rate data in later releases of MOVES) must adequately represent these bins.

As discussed in Section 4, the database used to develop MOVES2004 was heavily weighted with data collected with the IM240 test procedure. As a result, the distribution of operation time by VSP bin in the MOVES2004 database mirrors that of the IM240 test, which has a top speed of 56.7 mph and a maximum VSP in the high-speed region (i.e., over 50 mph) of about 18 kW/tonne for an "average" passenger car. Although the average amount of time spent above 50 mph and above 18 kW/tonne amounts to about 6% of travel time nationally, this operating mode has a significant impact on overall emissions. We estimate that this high-speed/high-VSP operation accounts for about 20% of HC and NOx emissions and about 40% of CO emissions (based on the existing MOVES2004 database). Thus, it is very important for these operating modes to be adequately populated. It is clear that EPA's future data collection efforts need to be focused at high-speed/high-VSP operation.

In concept, the general VSP binning approach seems reasonable. However, our review has identified several issues associated with the MOVES2004 activity data. As noted above, with respect to the allocation of vehicle starts to the county level, the model should not be using Interstate and freeway VMT, as vehicle starts are not generally occurring on these roadways. To illustrate the problems with this approach, consider a rural county where a high fraction of total county VMT is associated with travel on an interstate used primarily for long-distance travel. In this case, the current methodology would lead to an overestimation of starts and therefore starting emissions.

Relative Distributions of VMT and Fuel Consumption Data by VSP Bin – Earlier in this section, the distribution of VMT by VSP bin for nationwide rural, urban and overall driving was presented. In Section 4, the distribution of fuel consumption data that underlies MOVES2004 as a function of VSP bin was presented and compared to the national average distribution of travel time spent in each bin (urban and rural combined). It is important to compare these distributions to determine how the distribution of fuel consumption data compares to the distribution of VMT because a key issue for the accuracy of MOVES is that the supporting fuel consumption rate data (and emission rate data in later releases of MOVES) must adequately represent the high VMT bins. The concern is that if there are relatively few fuel consumption data in a bin that has a substantial VMT allocation, the accuracy of the resulting predictions may be questionable. This issue was discussed in Section 4 and is further assessed below.

In order to investigate this issue, we have subtracted the percentage of the total fuel consumption data in each VSP bin from the percentage of VMT attributed to each bin for the nationwide average rural, urban and overall cycles as shown in Table 6-7. As a result, in Table 6-7, a large positive value means that percentage of total fuel consumption data in that bin is much greater than the percentage of VMT allocated to that bin. Conversely, a large negative number means that the percentage of total fuel consumption data in that bin is much smaller than the percentage of VMT allocated to the bin. While this approach is semi-quantitative at best, it does highlight those bins for which the collection/generation of additional fuel consumption (and emissions) data should be considered.

As shown, in Table 6-7, it appears that the generation/addition of more data should be considered for the high speed bins, 33, 35, and 36 and for the idle conditions represented by bin 1. The need for additional high speed data would probably appear to be even greater if this comparison had been made using the "new" EPA binning strategy discussed in Section 4.

| Table 6-7<br>Differences in the Distribution of<br>Fuel Consumption Data and VMT by VSP Bin | | | |
|---|---|---|---|
| Bin | Data -VMT Rural (%) | Data -VMT Urban (%) | Data- VMT Overall (%) |
| 0 | 6.42 | 3.69 | 4.40 |
| 1 | 0.34 | -10.88 | -7.95 |
| 11 | 3.39 | -0.20 | 0.74 |
| 12 | 4.54 | -1.36 | 0.18 |
| 13 | 3.58 | 1.57 | 2.09 |
| 14 | 2.32 | 1.38 | 1.63 |
| 15 | 2.53 | 1.81 | 2.00 |
| 16 | 1.02 | 0.51 | 0.64 |
| 21 | -1.19 | -1.84 | -1.67 |
| 22 | 1.43 | 1.01 | 1.12 |
| 23 | 8.16 | 7.52 | 7.69 |
| 24 | -0.82 | -1.10 | -1.03 |
| 25 | -0.51 | -0.81 | -0.73 |
| 26 | 1.21 | 1.00 | 1.06 |
| 33 | -6.25 | -1.05 | -2.41 |
| 35 | -6.36 | 0.87 | -1.02 |
| 36 | -19.61 | -2.02 | -6.62 |

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# 7. EVALUATION OF MOVES2004 FUEL CONSUMPTION ESTIMATES

In this section, we first discuss the results of our critical review of the work that EPA has performed to evaluate or "validate" the fuel consumption estimates generated by MOVES2004. In addition, we discuss the results of our independent efforts to evaluate the accuracy of fuel consumption estimates generated by the MOVES and PERE models for three current technology vehicles that generally span the light-duty vehicle size range operating over several driving cycles representative of the range of normal vehicle operation.

## 7.1 Summary of EPA's Validation of MOVES2004 Fuel Consumption Estimates

EPA's efforts to validate MOVES2004 are documented in the report "MOVES Validation Results."[9] In that report, EPA presents results from two basic analyses. In the first analysis, EPA compared MOVES2004 predictions of fuel consumption for calendar years 1999 to 2002 to estimates published by the Federal Highway Administration (FHWA) for the same year. In the second analysis, EPA compared MOVES2004 estimates of fuel consumption by vehicle type and model year to those published in the most recent EPA fuel economy trends report,[10] and model-year-specific fuel consumption estimates published by FHWA.

With respect to the first EPA analysis, Table 7-1 presents the results of EPA's comparison of MOVES2004 estimates of nationwide gasoline and Diesel fuel consumption by on-road vehicles during 1999 to 2002 to values published by FHWA. The FHWA values are based on state tax records, which are submitted to FHWA. FHWA adjusts the data by subtracting non-highway fuel use from the total use reported by the states and making other, more minor, adjustments. The MOVES2004 estimates were generated by EPA by exercising the model on a state-by-state and monthly basis and then aggregating the results. As MOVES2004 estimates energy consumption, this output was converted to gallons of gasoline and Diesel fuel using lower heating values for gasoline and Diesel. In estimating the heating value for gasoline, EPA used the national average mix of conventional reformulated gasoline.

| Table 7-1<br>Annual Nationwide Fuel Consumption, FHWA and MOVES2004<br>(billion gallons) | | | | | | |
|---|---|---|---|---|---|---|
| Year | Gasoline | | | Diesel | | |
| | FHWA | MOVES | %Diff | FHWA | MOVES | %Diff |
| 1999 | 128.7 | 126.6 | -2% | 31.9 | 30.8 | -3% |
| 2000 | 128.9 | 127.9 | -1% | 33.4 | 32.0 | -4% |
| 2001 | 129.7 | 129.0 | -1% | 33.4 | 32.7 | -2% |
| 2002 | 133.0 | 131.5 | -1% | 34.8 | 33.8 | -3% |

As shown in Table 7-1, the MOVES2004 estimates for nationwide fuel consumption agree well with the FHWA values. However, while this method does allow for the evaluation of the accuracy of nationwide MOVES2004 fuel consumption estimates for the entire vehicle fleet, it does not validate the MOVES2004 estimates of fuel consumption for individual model years, nor does it validate the model's assumptions by vehicle class and VSP bin.

EPA did, however, also evaluate state-by-state differences between MOVES2004 estimates and FHWA values for calendar year 2002. The MOVES results for gasoline consumption ranged from a 19% underestimation of fuel consumption for New Hampshire to a 34% overestimation of fuel consumption for Washington, D.C. Variations in MOVES2004 Diesel fuel consumption estimates relative to FHWA values were greater. EPA speculates that the state-by-state differences could be due to cross-state travel, i.e., for some vehicles, particularly in the Northeast, fuel can be purchased primarily in one state and used mostly in another. However, even for California, which has the highest fuel consumption of any state and where cross-state travel effects should be minimal, MOVES2004 underpredicted fuel consumption by 11% relative to the FHWA data.

EPA's validation effort also involved comparisons of MOVES2004 estimates of 2002 calendar-year fuel consumption by vehicle class to similar estimates based on the FHWA data. In this case, the estimate based on the FHWA data was generated by dividing total gallons of fuel consumed by estimates of total vehicle miles traveled (VMT0 by vehicle type obtained from the Highway Performance Management System, HPMS). However, because the MOVES2004 model also uses VMT from the HPMS, this is not really an independent comparison, as EPA acknowledges. The MOVES2004 and FHWA estimates are shown in Table 7-2. As shown, MOVES2004 somewhat overestimated passenger car fuel economy and somewhat underestimated light-truck fuel economy relative to the FHWA estimates.

| Table 7-2<br>2002 U.S. Fleetwide Fuel Economy from FHWA and MOVES2004 | | | |
|---|---|---|---|
| Vehicle Class | FHWA | MOVES | % Difference |
| Passenger cars | 22.0 | 22.8 | 4% |
| Light Trucks | 17.4 | 16.6 | -5% |

Turning to EPA's second analysis, Figures 7-1 and 7-2 present EPA's comparisons of fuel economy estimates by model year from MOVES2004 to published fuel economy values from the Fuel Economy Trends report (reference 10 – referred to as F.E. Trends in the figures), for passenger cars and light-duty trucks, respectively. The MOVES2004 estimates were generated by running the model on an annual and a national basis for calendar year 2004, and specifying the output at the model year level. In addition, the values from reference 10 were reduced by 15% in order to account for differences between standard EPA fuel economy estimates and actual in-use fuel economy.

**Figure 7-1**
**Passenger Car Fuel Economy by Model Year for Fuel Economy Trends Report and MOVES2004 (MPG)**

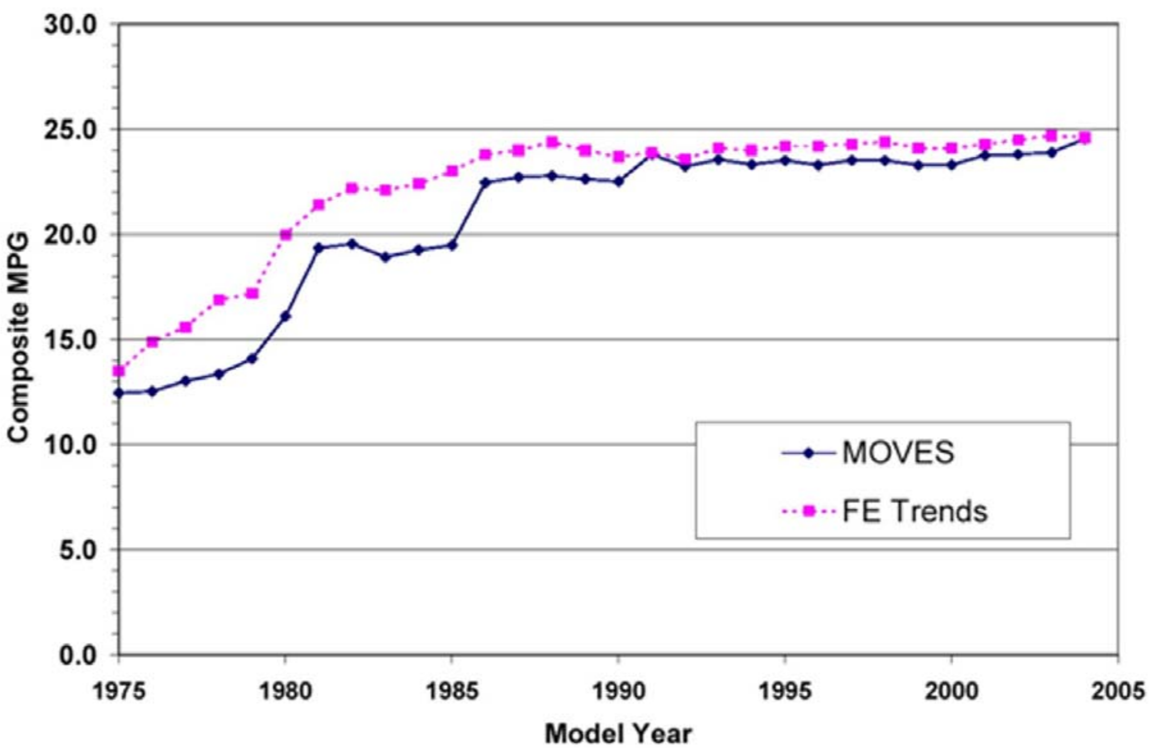
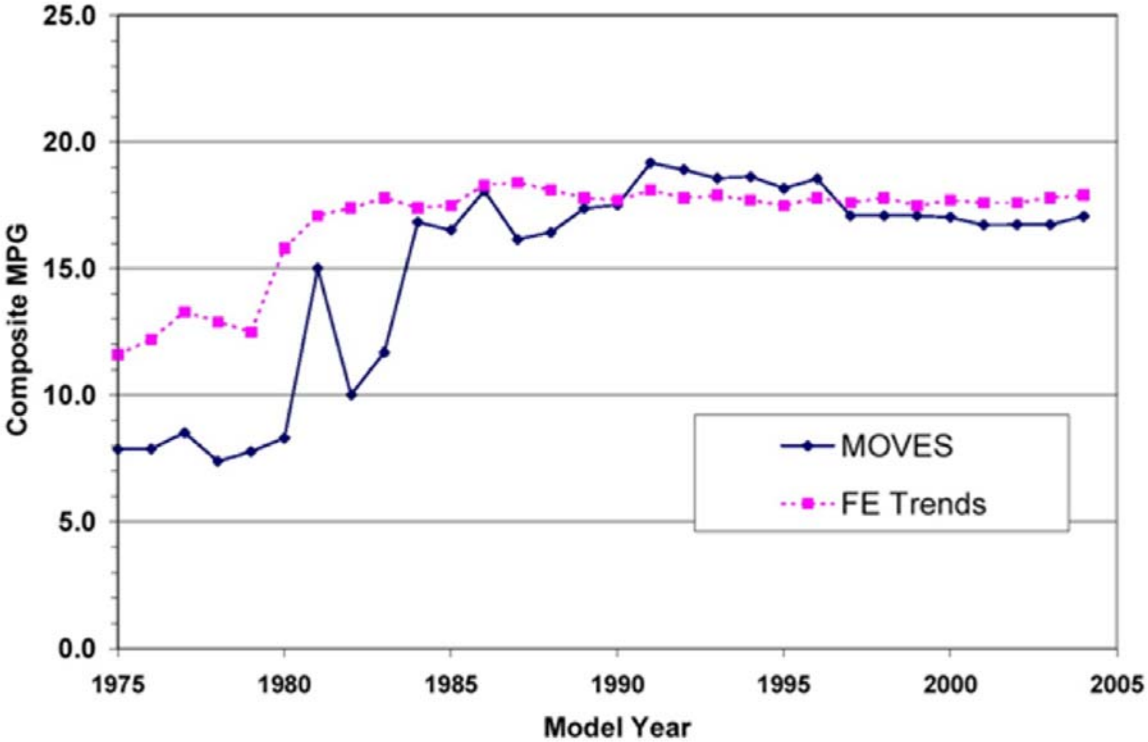


**Figure 7-2**
**Light-Truck Fuel Economy by Model Year for Fuel Economy Trends Report and MOVES2004 (MPG)**




Figures 7-1 and 7-2, taken directly from reference 1, show that for passenger cars, MOVES2004 fuel economy estimates are somewhat less than EPA reported for pre-1990 model years, but very nearly equal to the report values for 1990 and later model years. MOVES2004 estimates for light-duty trucks show that fuel economy values for pre-1985 model year vehicles that are significantly less than EPA reported, but for 1985 and later model years the MOVES2004 values are in good agreement with the reported values.

EPA speculates that the reason for the consistently lower fuel economy estimates for passenger cars from MOVES2004 could be due to the simplistic methodology used to adjust the data from reference 10 to reflect actual in-use fuel economy. However, if this were the case, one would expect to see a more consistent difference across all the model years. Instead, as shown in Figure 7-1, differences between the MOVES2004 values and those from reference 10 are much smaller for the 1990 and later model years than the pre-1990 model years. One possible explanation for this is the widespread use of ported fuel injection on 1990 and later model-year vehicles, which could have improved in-use fuel economy under cold starts at cold temperature conditions, or reduced the frequency of "rich" in-use failures. This effect would not be reflected in data from reference 10, which were obtained at temperatures between 68º and 86º F on vehicles in good operating condition.

For light-duty trucks, EPA believes that the large swings in MOVES fuel economy in the early 1980s can be traced to anomalies in truck weight data as derived from the VIUS and Oak Ridge Lab datasets. EPA further believes the large drop from 1996 to 1997 is due to the introductions of heavier trucks in the 1997 model year, like the Ford Expedition. But EPA's explanations ignore the fact that, as shown in Figure 7-2, MOVES2004 fuel economy estimates of 1990 and later model-year light-duty trucks are much closer to the data from reference 10 than for pre-1990 model years. Again, it seems that the explanation for this result might lie in changes in vehicle technology.

EPA also forwards no explanation as to why MOVES estimates for LDTs are so much lower than the Trends Report for 1984 and earlier model years. The differences are as much as 30-40%. Clearly, the MOVES model appears to significantly underestimate LDT fuel economy for these years. While these vehicles are less important to the fleet with each passing year, they are important if fuel consumption or criteria pollutant emissions are ever backcast earlier than 1999. EPA should thoroughly investigate why its estimates are so much different than the Trends Report for these years, and change these estimates, if necessary.

EPA's overall conclusions regarding its evaluation of MOVES2004 fuel economy estimates, as published in reference 9, were that "the comparisons presented in this report are encouraging, particularly the good agreement between fuel consumption estimates derived from MOVES and the top-down fuel sales data compiled by FHWA."

While the fuel consumption and fuel economy comparisons presented by the EPA tend to show reasonable agreement with other data, we would expect fuel consumption and fuel economy to be the easiest parts of the model to develop and validate, since the model is based on vehicle specific power, and these items (fuel economy and fuel consumption) are not influenced by catalytic converter systems. We would expect the validation to be much more difficult for VOC, CO, and NOx.

## 7.2 Peer Review of the EPA MOVES2004 Validation Effort

Professor Rob Harley of the Department of Civil and Environmental Engineering at the University of California at Berkeley reviewed the EPA validation published in reference 9. Professor Harley made a number of comments on the report, which, in our opinion, EPA has adequately addressed. However, EPA did not change the title of the report as Harley requested to highlight the fact that the ability of MOVES2004 to predict emissions of criteria pollutants has not been evaluated. More substantively, Harley recommended that EPA extend its comparison of MOVES2004 and FHWA national on-road fuel consumption estimates beyond the 1999–2002 period to earlier years to determine if MOVES2004 accurately estimates retrospective trends in gasoline and Diesel fuel usage. EPA's response was:

> *The earliest calendar year MOVES2004 can currently provide estimates for is 1999, so the suggested comparison isn't currently possible.*

This is not an adequate response to Harley's comment and we believe that EPA should demonstrate that MOVES2004 can accurately predict historical trends in on-road vehicle fuel economy as part of its efforts to validate the performance of the model.

## 7.3 Bottom-Up Evaluation of MOVES2004 Fuel Consumption Estimates

As described above, the EPA MOVES2004 validation effort focused on very broad comparisons of MOVES estimates with national fuel consumption, state-by-state fuel consumption, and model year specific fuel economy values on a national- and annual-average basis. These "top-down" comparisons showed reasonable agreement; however, as indicated, they do not independently validate either the MOVES2004 vehicle activity or the fuel economy estimates, but rather the product of these two estimates, which is fuel consumption. EPA has performed no "bottom-up" validation of MOVES2004 examining the performance of the model in predicting fuel consumption of individual vehicles over specific driving cycles, which would eliminate vehicle activity estimates as a potential confounding variable.

Given this, we have generated MOVES2004 predictions of fuel consumption for the same three late model vehicles and driving cycles used in our evaluation of the PERE model, as discussed in Section 5. As noted in Section 5, PERE is used to fill data holes in MOVES2004, particularly for future model years. The key difference between MOVES2004 and PERE estimates is that MOVES is based on a 10,000-vehicle database of second-by-second test results, and PERE estimates are based on typical parameters for the three vehicles. In the case of these three 1998 to 1999 model-year vehicles, MOVES2004 contains a considerable amount of actual fuel consumption data and the evaluation presented below in fact represents a comparison of the data-driven performance of MOVES2004, rather than just a rehash of our evaluation of the performance of the PERE model.

One potential concern with this comparison is that the MOVES model is designed to predict emissions for a fleet of vehicles, and not necessarily individual vehicles. However, the method we used to make these comparisons eliminates much of this concern. Basically, the MOVES model has separate fuel economy estimates by model year, weight, and engine size. In our comparison, we are utilizing the specific fuel consumption values in the model that directly compare with our three vehicles. And, we have picked vehicles that are not unusual vehicles in their respective weight ranges; therefore, these comparisons should be appropriate. The methods used in this comparison are further described below.

As described in Section 3, MOVES2004 is designed to estimate fuel consumption for a fleet of vehicles operating in a particular geographical area at a certain point or points in time. It also provides estimates for a given geographical area on a year-specific basis. However, the model does not directly output second-by-second fuel consumption estimates for a single vehicle, although such data are generated within the model. In order to extract these estimates, the following process was used:

a. First, the specific source bin that would apply to each of the three vehicles (vehicle class, fuel type, engine technology, model year range, and loaded vehicle weight range) was identified. These source bins are shown in Table 7-3.

**Table 7-3**
**MOVES Source Bin Definitions Used in the Evaluation**

| Vehicle | Fuel Type | Engine Technology | Model Year Group | Loaded Weight Range | Engine Size Range (L) |
|---|---|---|---|---|---|
| Camry | Gasoline | Conventional IC | 1991-2000 | 3001-3500 | 2.1-2.5 |
| Suburban | Gasoline | Conventional IC | 1991-2000 | 6001-7000 | >5.0 |
| Taurus | Gasoline | Conventional IC | 1991-2000 | 3501-4000 | 2.6-3.0 |

b. The energy consumption values by VSP bin for these source bins were extracted from the MOVES model.

c. The rolling "A," rotating "B," drag "C" coefficients, and vehicle mass values used by the MOVES model to estimate VSP for a given driving cycle identified and extracted from the model. Those values are presented in Table 7-4.*

**Table 7-4**
**VSP Parameters from MOVES**

| | Cars | Light-Duty Trucks |
|---|---|---|
| Rolling "A" | 0.156461 | 0.221120 |
| Rotating "B" | 0.00200193 | 0.00283757 |
| Drag "C" | 0.000492646 | 0.000698282 |
| Mass (1000 KG) | 1.4788 | 1.86686 |

* We note that MOVES2004 appears to use these same values for all cars and light-duty trucks. However, the model also contains a regression expression that relates the A, B, and C coefficients to vehicle weight, vehicle class, and track load horsepower. The values in Table 7-4 were used for the comparison presented here, but second-by-second VSP and fuel consumption were also computed using these regression equations. The use values from the regression equations, rather than the values in Table 7-3, had little effect on the results.

d. The values in Table 7-4 were used with the second-by-second speed data for the three driving cycles to estimate second-by-second VSP for each of the three vehicles over each driving cycle using the MOVES2004 VSP equation.

e. The second-by-second VSP values were then combined with the energy consumption values by VSP from step 2 to estimate second-by-second energy consumption.

f. Finally, the energy consumption values were converted to fuel consumption values using constants obtained from the EPA MOVES reports.

For the FTP driving cycle, energy consumption values from Bags 2 and 3 were used to develop the VSP bin and second-by-second energy consumption values. For the other two cycles, the energy consumption values from the entire cycle were used to develop the VSP bin and second-by-second energy consumption values.

The MOVES2004 fuel consumption estimates for the three vehicles over each of the three driving cycles are shown in Figures 7-3 to 7-11. Figures 7-3, 7-4, and 7-5 show results for the 1998 Toyota Camry over the FTP, LOSA, and Unified Cycles, respectively. Figures 7-6 to 7-8 show results for the 1999 Suburban, while Figures 7-9 to 7-11 present the results for the 1999 Taurus.

**Figure 7-3**

**Actual vs PERE, VEHSIM and MOVES Cumulative Fuel Consumption**
**1998 Camry, FTP Hot Mode, Actual TRLHP**

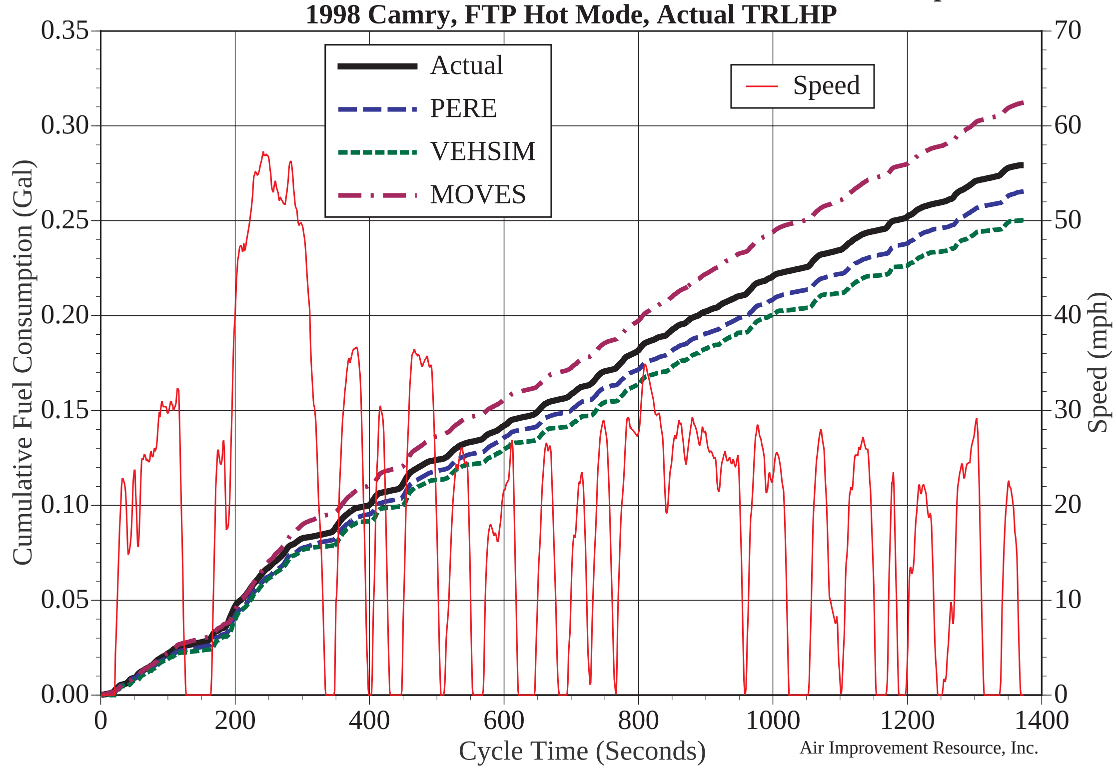


**Figure 7-4**
**Actual vs PERE, VEHSIM and MOVES Cumulative Fuel Consumption**
**1998 Camry, LOSA Test 1, Actual TRLHP**

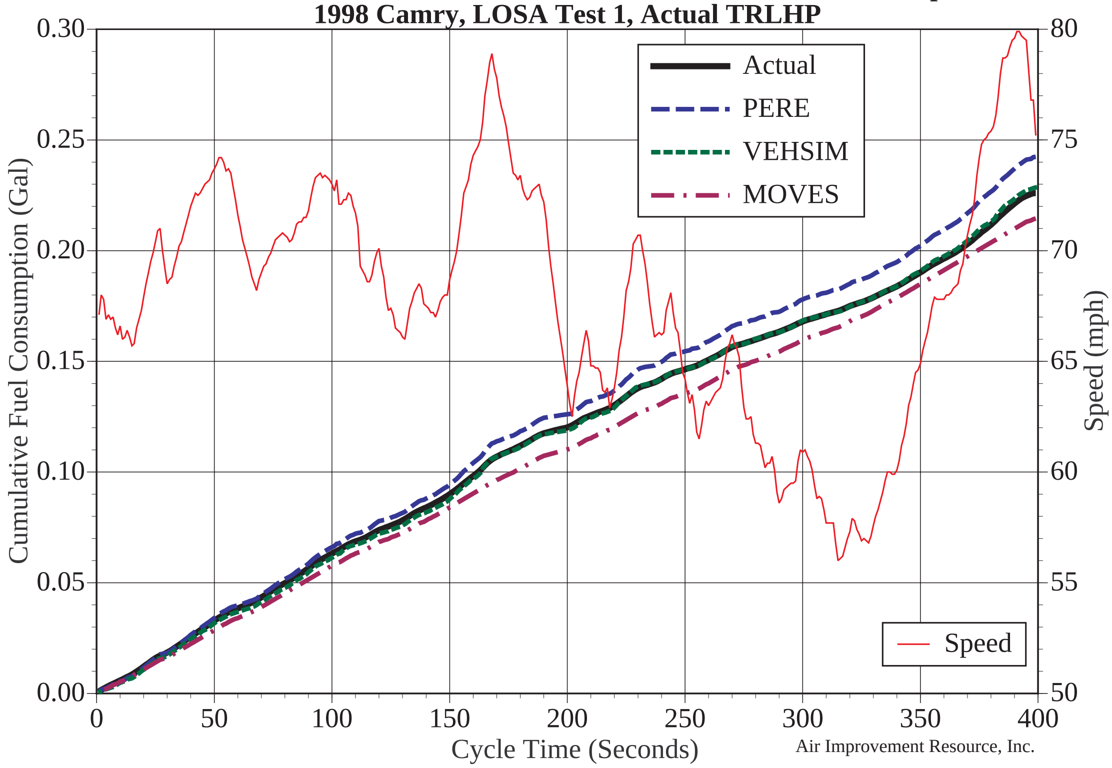



**Figure 7-5**
**Actual vs PERE, VEHSIM and MOVES Cumulative Fuel Consumption**
**1998 Camry, UC Test 1, Actual TRLHP**

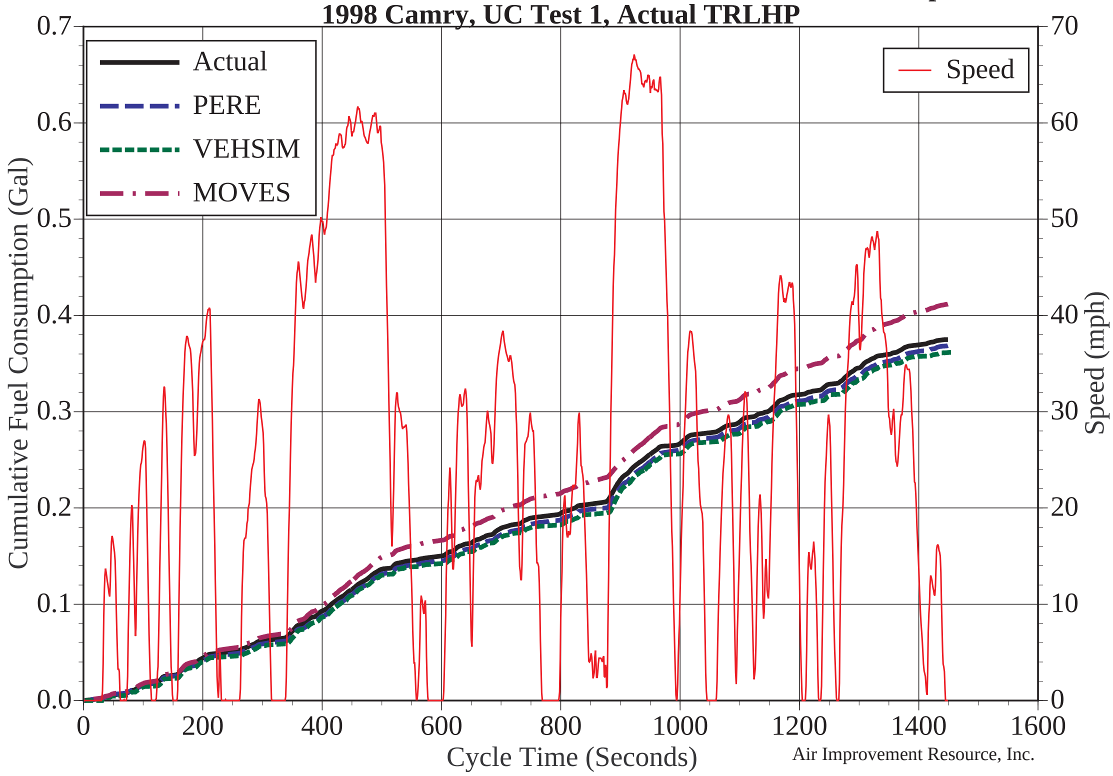


**Figure 7-6**
**Actual vs PERE, VEHSIM and MOVES Cumulative Fuel Consumption**
**1999 Suburban, FTP Hot Mode, Actual TRLHP**

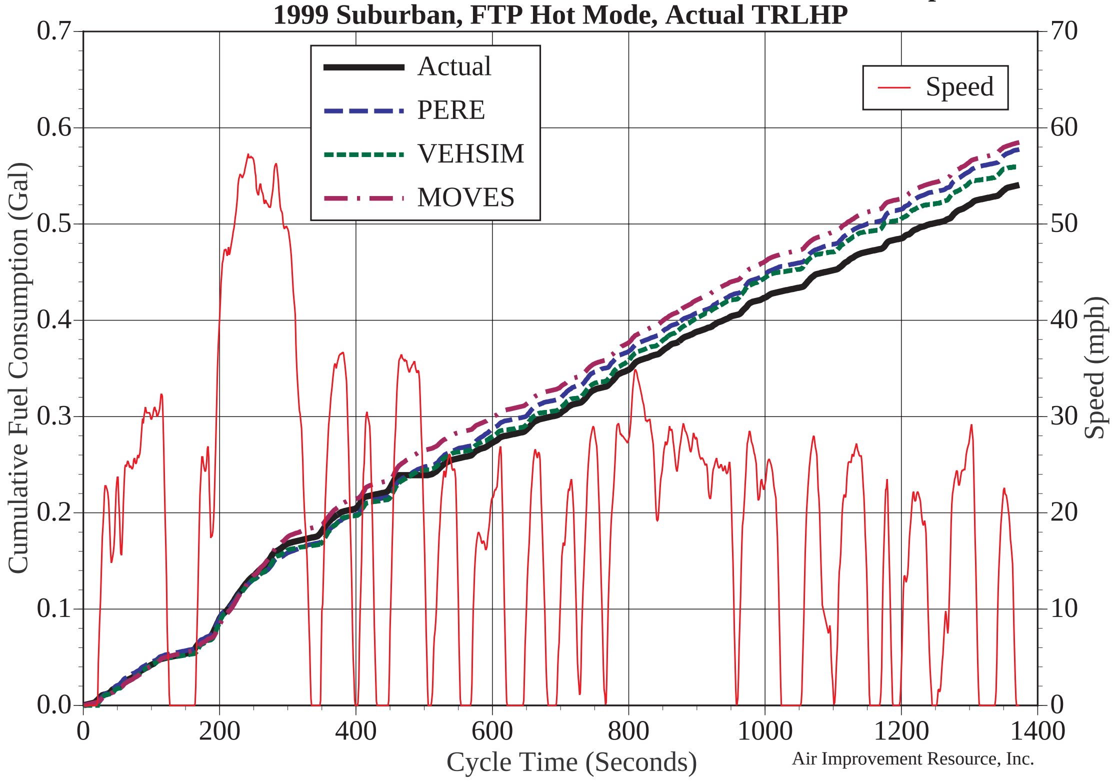



**Figure 7-7**
**Actual vs PERE, VEHSIM and MOVES Cumulative Fuel Consumption**
**1999 Suburban, LOSA Test 1, Actual TRLHP**

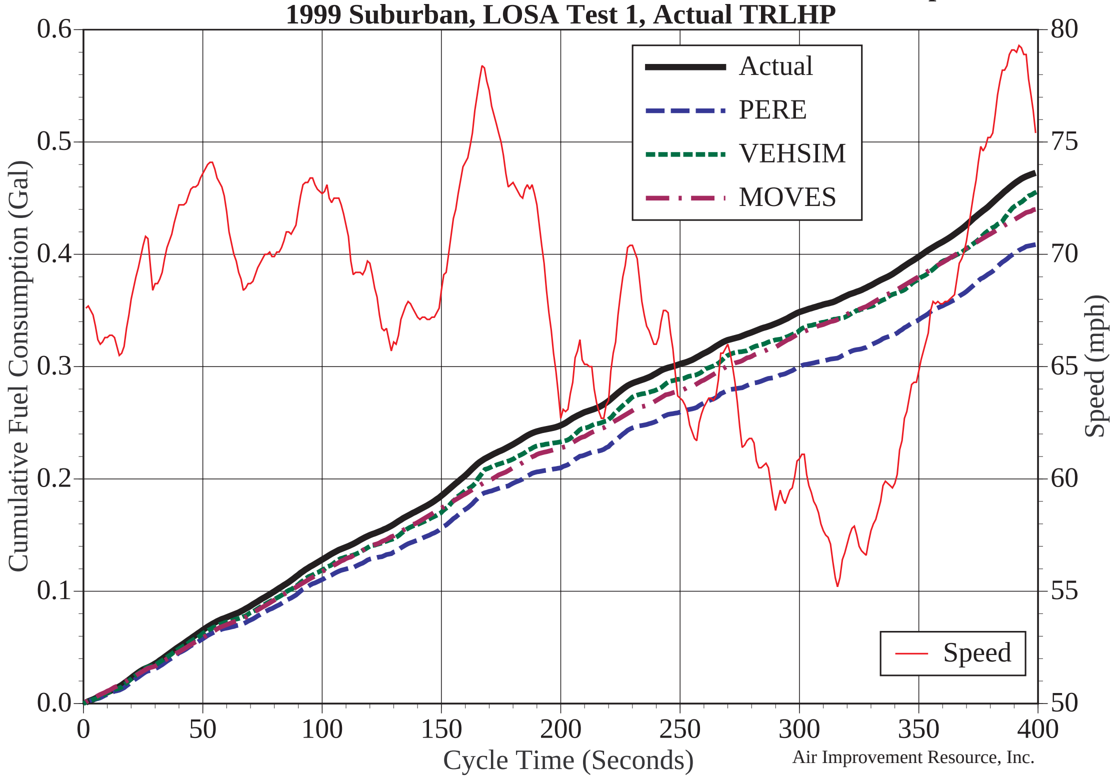


**Figure 7-8**

**Actual vs PERE, VEHSIM and MOVES Cumulative Fuel Consumption**
**1999 Suburban, UC Test 1, Actual TRLHP**

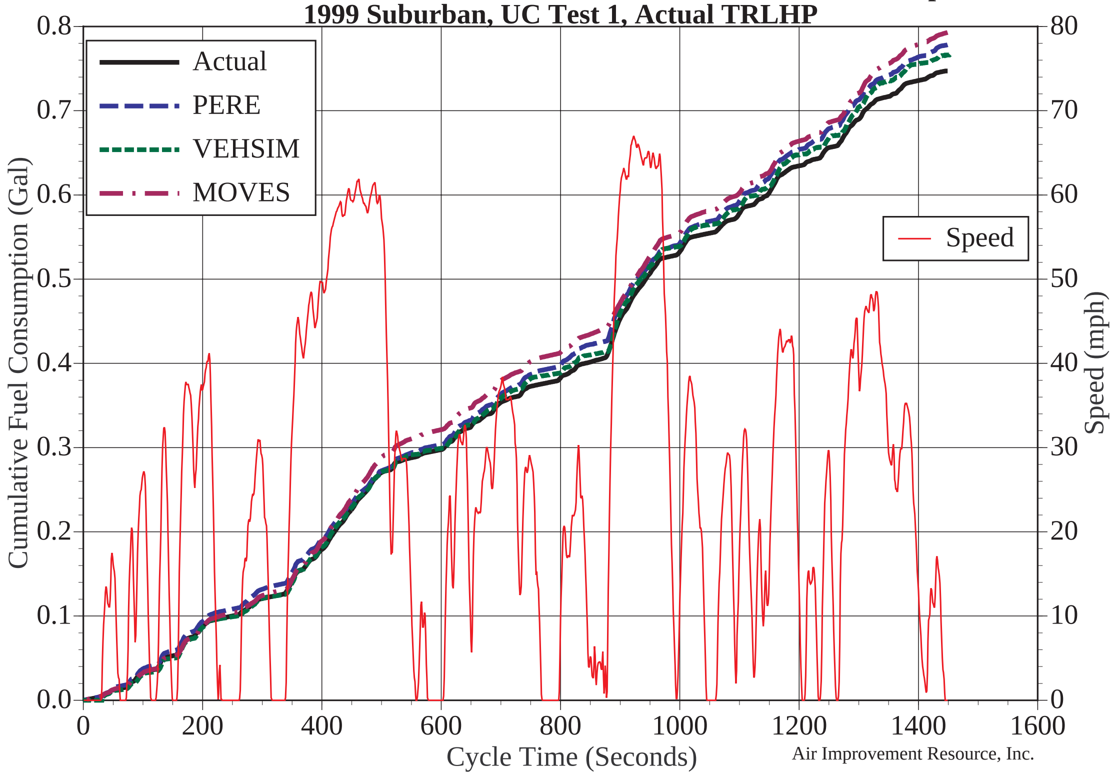



**Figure 7-9**

**Actual vs PERE, VEHSIM and MOVES Cumulative Fuel Consumption**
**1999 Taurus, FTP Hot Mode, Actual TRLHP**

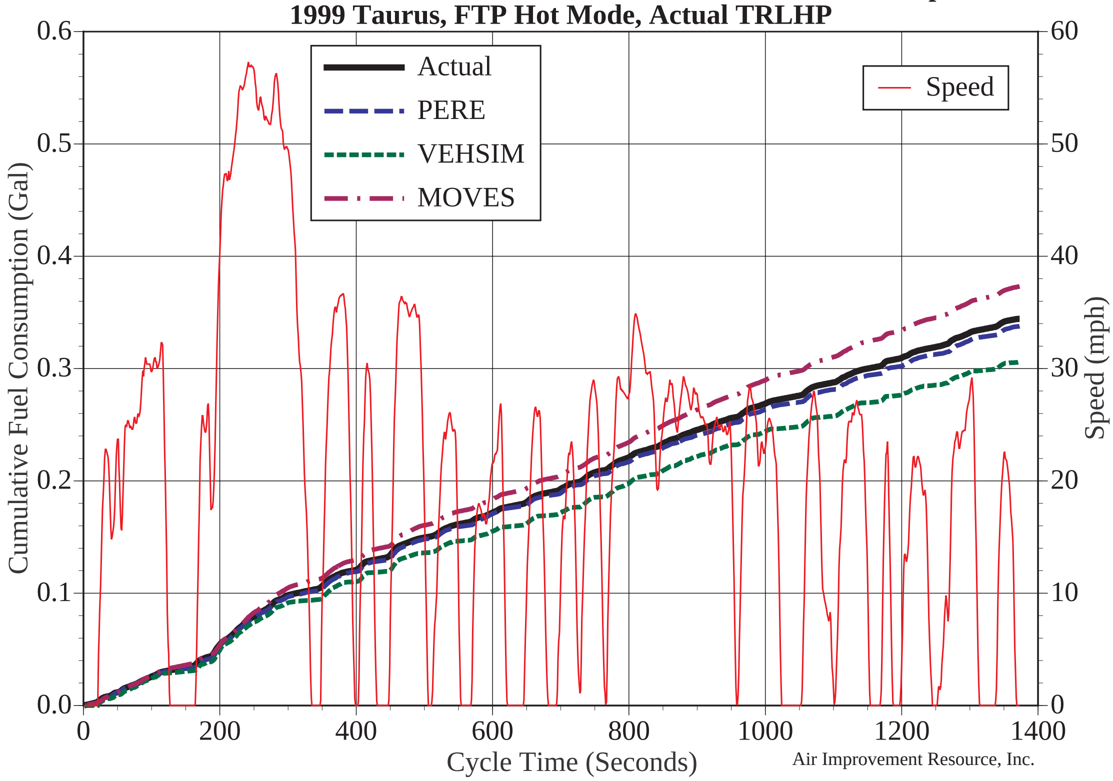


**Figure 7-10**

**Actual vs PERE, VEHSIM and MOVES Cumulative Fuel Consumption**
**1999 Taurus, LOSA Test 1, Actual TRLHP**

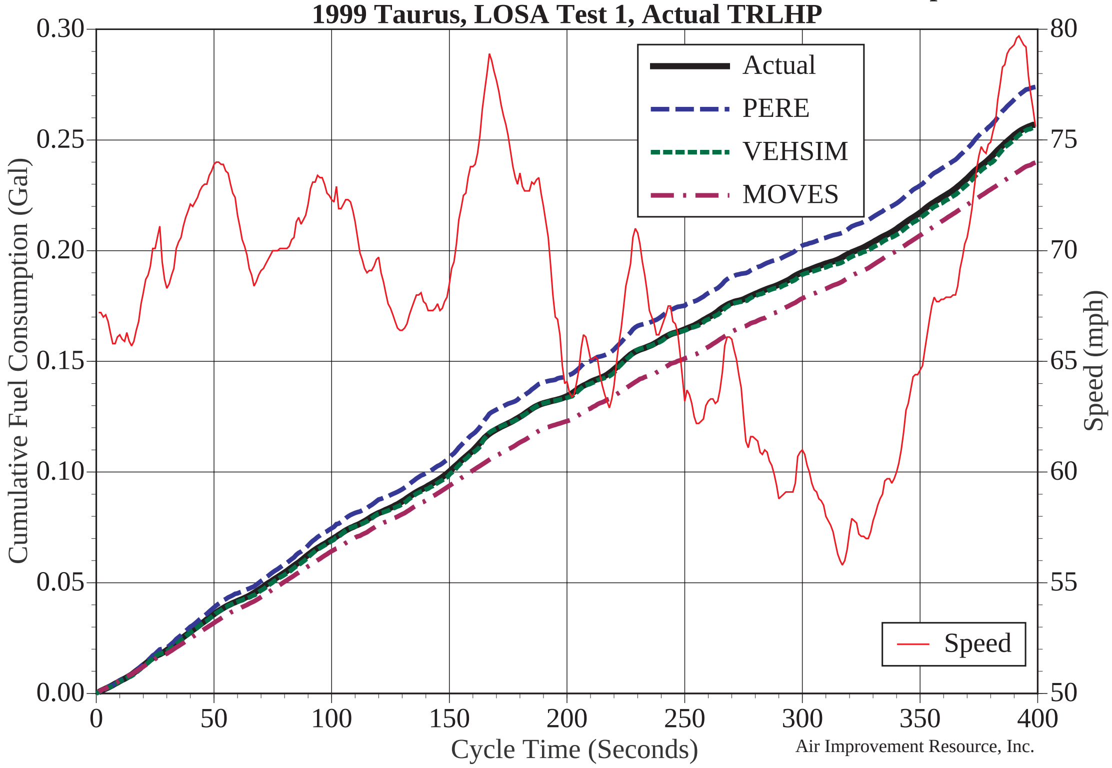
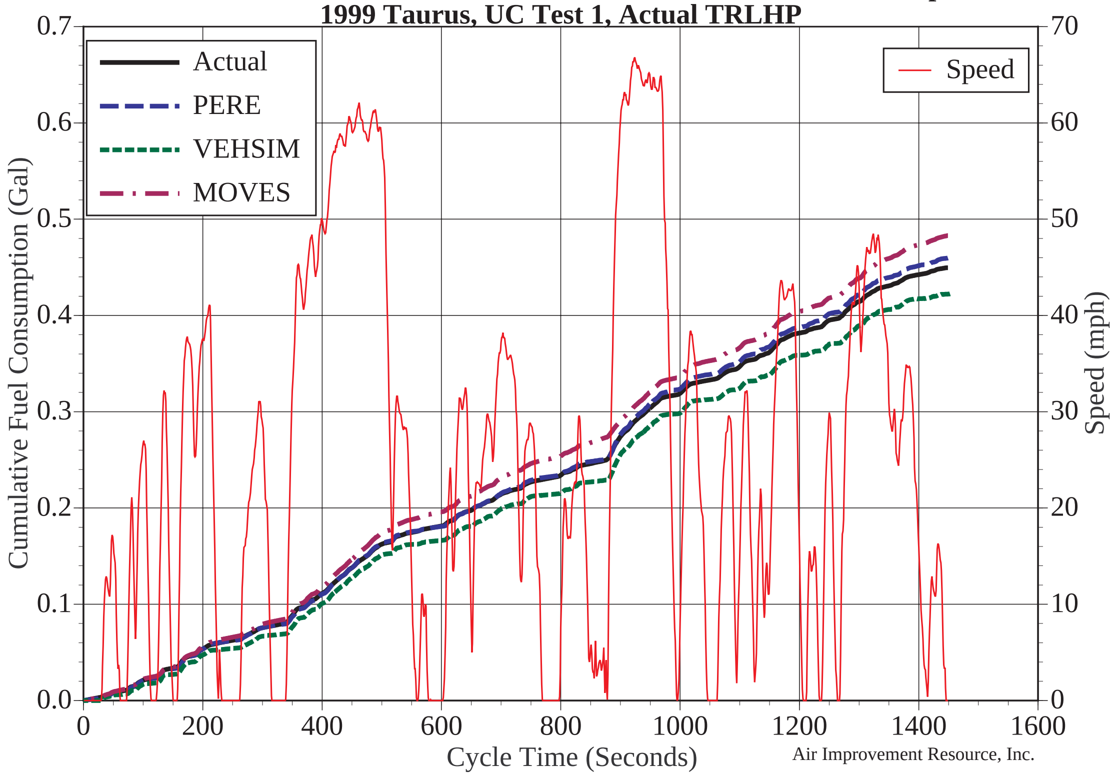



**Figure 7-11**

**Actual vs PERE, VEHSIM and MOVES Cumulative Fuel Consumption**
**1999 Taurus, UC Test 1, Actual TRLHP**



In addition to MOVES2004 estimates and actual fuel consumption, the estimates from the PERE and VEHSIM models presented in Section 5 are shown. Data summarizing the performance of each of the three models in predicting total fuel consumption over each cycle are presented in Table 7-5. Most of the percent differences between the models and the actual fuel consumption are within ±10%, except for the MOVES model for the hot FTP on the Camry and Taurus, the PERE model on the Suburban for the LOSA, and the VEHSIM on the Hot FTP for the Camry.

The most notable feature shown in the figures and Table 7-5 is that MOVES2004 overpredicts FTP and Unified Cycle fuel consumption for all three vehicles and underpredicts fuel consumption on the LOSA cycle for all three vehicles. The LOSA drive cycle differs from the FTP and Unified Cycles in that it has a higher average vehicle speed and does not have any stop-and-go operation. Therefore, it is possible that the MOVES2004 fuel consumption estimates are being biased by a lack of data at high speeds, a lack of data from relatively steady-state operation, or overestimating fuel consumption during stop-and-go operation. In contrast, there is no apparent pattern in the fuel consumption estimates from the PERE or VEHSIM models.

**Table 7-5**
**Comparison of Total Fuel Consumption Over Three Cycles**

| Vehicle | Cycle | Cycle Fuel Consumption (gallons) | | | | Percent Difference From Actual | | |
|---|---|---|---|---|---|---|---|---|
| | | Actual | MOVES | PERE | VEHSIM | MOVES | PERE | VEHSIM |
| Camry | FTP HOT | 0.279 | 0.312 | 0.266 | 0.250 | 11.8 | -4.9 | -10.4 |
| | LOSA | 0.225 | 0.215 | 0.242 | 0.229 | -4.6 | 7.8 | 1.7 |
| | UC | 0.382 | 0.412 | 0.367 | 0.362 | 7.8 | -3.9 | -5.3 |
| Suburban | FTP HOT | 0.548 | 0.585 | 0.577 | 0.560 | 6.8 | 5.4 | 2.2 |
| | LOSA | 0.473 | 0.440 | 0.409 | 0.458 | -7.0 | -13.7 | -3.3 |
| | UC | 0.744 | 0.793 | 0.774 | 0.767 | 6.5 | 4.0 | 3.0 |
| Taurus | FTP HOT | 0.338 | 0.373 | 0.337 | 0.306 | 10.4 | -0.3 | -9.6 |
| | LOSA | 0.255 | 0.240 | 0.274 | 0.256 | -6.1 | 7.2 | 0.3 |
| | UC | 0.445 | 0.483 | 0.459 | 0.422 | 8.6 | 3.1 | -5.0 |
| Average | FTP HOT | 0.388 | 0.423 | 0.393 | 0.372 | 9.0 | 1.3 | -4.2 |
| | LOSA | 0.318 | 0.298 | 0.308 | 0.314 | -6.1 | -2.9 | -1.0 |
| | UC | 0.524 | 0.563 | 0.533 | 0.517 | 7.4 | 1.8 | -1.3 |

While the results from these three vehicles do not conclusively demonstrate a problem or flaw with the MOVES2004 model, the apparent pattern of over- and underprediction of fuel economy by MOVES2004 for these three vehicles and driving cycles, coupled with the lack of a bottom-up validation of the model, is a major concern. As noted above, it could be that the basic MOVES methodology generates biased fuel consumption estimates for different types of driving cycles, which, if true, indicates that the methodology has significant flaws.  Further, if the methodology is incapable of generating accurate fuel consumption estimates, there is no reason to believe that it will be capable of generating accurate estimates of criteria pollutant emissions.

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# 8. EVALUATION OF MOVES2004 ESTIMATES OF METHANE AND NITROUS OXIDE EMISSIONS

As noted in Section 3, MOVES2004 estimates emissions of methane ($CH_4$) and nitrous oxide ($N_2O$) using a methodology that differs fundamentally from that used to estimate fuel consumption, and that in fact is a simplistic version of the general emissions estimation methodology used in the MOBILE series of models. This methodology essentially involves multiplying an emission factor or emission rate by an activity factor or activity rate to generate an emissions estimate. Given this and the discussion of MOVES2004 activity estimates in Section 6 of this report, our evaluation of MOVES2004 estimates of $CH_4$ and $N_2O$ emissions focuses on the emission rates incorporated into the model.

## 8.1 Summary of MOVES2004 Emission Rates for $CH_4$ and $N_2O$

The $CH_4$ and $N_2O$ emission rates contained in MOVES2004 were developed by ICF Kaiser under contract to EPA.[11] These emission rates were based on previous EPA estimates as well as on additional data supplied by EPA. Although emission rates have been developed for all classes of light- and heavy-duty vehicles, in this review we focus only on methane and nitrous oxide emission factors from gasoline-powered passenger cars, light-duty trucks, and heavy-duty vehicles.

EPA's recommended nitrous oxide and methane emission factors for LDGVs, LDGTs, and HDGVs for LEVs, Tier 1, and Tier 0 vehicles are shown in Table 8-1. Factors for oxidation catalyst, non-catalyst, or uncontrolled vehicles are not presented because the populations of these vehicles are small at present and will further decline into the future. Table 8-1 also shows, for reference, emission rate estimates for $CH_4$ and $N_2O$ published by the Intergovernmental Panel on Climate Change (IPCC).[12] The IPCC and FTP emission rates in g/mi are directly comparable. The "FTP" emission rates form the basis for the running and start emission factors that EPA has incorporated into MOVES2004. However, the running emissions are converted to g/hr for use in MOVES with vehicle activity that is in units of hours, rather than miles. This conversion is described by EPA in the documentation for the MOVES2004 model.[13]

| Table 8-1<br>**EPA Proposed Nitrous Oxide and Methane Emission Factors** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Nitrous Oxide | | | | Methane | | | |
| | IPCC g/mi | FTP g/mi | Run g/mi | Start g/start | IPCC g/mi | FTP g/mi | Run g/mi | Start g/start |
| Gasoline-Fueled Passenger Cars | | | | | | | | |
| LEVs | **0.028** | **0.012** | 0.000 | 0.090 | **0.040** | **0.013** | 0.009 | 0.032 |
| Tier 1 | **0.046** | **0.030** | 0.015 | 0.113 | **0.048** | **0.020** | 0.012 | 0.055 |
| Tier 0 | **0.082** | **0.054** | 0.042 | 0.092 | **0.064** | **0.066** | 0.062 | 0.034 |
| Gasoline-Fueled Light Duty Trucks | | | | | | | | |
| LEVs | **0.035** | **0.009** | 0.001 | 0.059 | **0.048** | **0.017** | 0.011 | 0.046 |
| Tier 1 | **0.058** | **0.067** | 0.041 | 0.200 | **0.056** | **0.034** | 0.023 | 0.082 |
| Tier 0 | **0.102** | **0.090** | 0.069 | 0.153 | **0.113** | **0.071** | 0.062 | 0.072 |
| Gasoline-Fueled Heavy-Duty Vehicles | | | | | | | | |
| LEVs | **0.113** | **0.019** | 0.002 | 0.120 | **0.071** | **0.034** | 0.022 | 0.094 |
| Tier 1 | **0.139** | **0.138** | 0.083 | 0.409 | **0.097** | **0.047** | 0.024 | 0.163 |
| Tier 0 | **0.175** | **0.183** | 0.142 | 0.313 | **0.121** | **0.218** | 0.194 | 0.183 |

For $N_2O$, the EPA emission rates are lower than the IPCC rates, except for Tier 0 heavy-duty vehicles, where the proposed emissions are only slightly higher than the IPCC estimates. For methane, the EPA LEV and Tier 1 emission rates are lower than IPCC rates, but the Tier 0 emission rates for passenger cars are slightly higher, and the rates for Tier 0 heavy-duty gasoline vehicles are significantly higher. Finally, we note that the EPA $N_2O$ emission rates for light-duty trucks certified as LEVs are lower than for passenger cars certified as LEVS, which is not what one would expect given that the NOx standard for heavier light-duty trucks is higher than that for passenger cars and lighter light-duty trucks.

One problem with the EPA emission rates is that the database used by ICF to develop the emission rates presented in Table 8-1 does not clearly document the original sources of the data. In addition, there are few emissions data for either nitrous oxide or methane contained in the database for Tier 1 and LEV vehicles, and no data for Tier 2 vehicles. This can be seen in Tables 8-2 and 8-3, which show the size of the complete database for $CH_4$ and $N_2O$ as well as the size of the database for Tier 1 and LEV vehicles. Also, it isn't clear from the available data whether the vehicles labeled as "LEVs" were certified to CARB LEV I or LEV II standards, although it is likely that all the vehicles were certified to LEV I standards. Finally, it is not clear what fuels were used in the various tests. Given that fuel sulfur would be expected to affect emissions of both compounds, it would not be appropriate to mix data from tests that used high-sulfur fuel with data from tests on lower sulfur fuel on vehicles certified to Tier 1 or more stringent standards.

| Table 8-2<br>Total Sample Sizes | | | |
|---|---|---|---|
| Pollutant | Test Type | Vehicles | Tests |
| $CH_4$ | FTP | 6,950 | 13,277 |
| | Non-FTP | 2,963 | 14,636 |
| $N_2O$ | FTP | 64 | 95 |
| | Non-FTP | 232 | 74 |

| Table 8-3<br>Sample Sizes for Tier 1 and LEVs | | | | |
|---|---|---|---|---|
| Pollutant | Test Type | Technology | Passenger Cars | LDTs |
| $CH_4$ | All | Tier 1 | 131 | 80 |
| | All | LEVs | 7 | 10 |
| $N_2O$ | All | Tier 1 | 12 | 16 |
| | All | LEVs | 7 | 5 |

Finally, as noted previously, ICF has made no effort to develop temperature correction factors for either compound. However, EPA has indicated that such factors may be developed in the near future.

The evaluation of MOVES2004 with respect to its estimates of $CH_4$ and $N_2O$ emissions during the peer review process was conducted by Tom Durbin, an Associate Research Engineer at CE-CERT at the University of California, Riverside.[11] The following is a a summary of Durbin's most significant comments:

1. There are a number of $CH_4$ and $N_2O$ studies that were not included in the database.

2. The $N_2O$ emission rates for light-duty trucks certified as LEVs should not be lower than that for cars certified as LEVs.

3. Fuel sulfur affects $N_2O$ emissions and that effect needs to be taken into account.

4. EPA has not discussed how $N_2O$ emission factors could change over different driving cycles relative to the FTP.

5. EPA has not addressed the issue of whether $CH_4$ and $N_2O$ emissions increase as vehicles accumulate mileage.

6. $CH_4$ and $N_2O$ emissions change as a function of temperature but that is not accounted for in MOVES2004.

EPA has responded that the Agency will address all of these comments in future versions of MOVES, something that we endorse.

## 8.2 Critical Review of MOVES2004 $N_2O$ Emission Rates

As part of this effort, we have critically reviewed the $N_2O$ emission rates used in MOVES2004. This review led to the identification of a number of concerns:

1. A number of $N_2O$ testing programs tested vehicles on both high- and low-sulfur fuels. Other testing programs used only higher sulfur fuels, like Clean Air Act baseline gasoline. Data from different programs with varying sulfur levels could have been inappropriately combined in the ICF analysis.

2. It appears that emission rates from LEV I and LEV II vehicles have been assumed to be the same. LEV II vehicles are subject to much lower NOx emission standards than LEV I vehicles; thus, it is possible their $N_2O$ emissions may be lower than those observed for LEV I vehicles. For example, Table 8-1 shows that MOVES2004 $N_2O$ emission factors for LEVs are much lower than Tier 1 vehicles. Further, the LEV NOx standard is 0.2 g/mi while the Tier 1 NOx standard is 0.4 g/mi. This strongly indicates that LEV II vehicles, which are subject to a NOx standard of 0.05 g/mi, should have lower $N_2O$ emissions than LEV I vehicles.

3. Emissions of $N_2O$ from Tier 2 vehicles are not separately estimated. Based on the above, Tier 2 vehicles, which are subject to significantly lower NOx standards than Tier 1 vehicles, would be expected to have much lower $N_2O$ emissions. Further, MOVES2004 needs to account for the fact that the Tier 2 fleet average NOx standard applies to all vehicles under 8,500 lbs GVW, including medium-duty passenger vehicles.

4. The model should be modified so that $N_2O$ emission rates vary with sulfur level, and sulfur level should be an input to the model, just like it is in the latest versions of the MOBILE series of models.

These concerns are discussed in more detail below.

Fuel Sulfur Effects - Appendix A of the Methane and Nitrous Oxide report indicates that ICF used data from EPA, ARB, Southwest Research, and UC/Riverside CE-CERT.[11] However, this appendix did not detail the types of vehicles tested nor the types of fuels used in the testing. The EPA testing program tested LEVs on Indolene (sulfur in 10-20 ppm range), and Tier 1 and older vehicles on Clean Air Act Baseline gasoline, with a sulfur level of about 300 ppm.[12,14] The UC Riverside testing involved a number of LEVs and at least one Tier 1 vehicle on both low- and high-sulfur fuels.[15] It appears that the variations in fuel sulfur content were not accounted for in any way by ICF in developing the $N_2O$ emission rates used in MOVES2004.

The impact of fuel sulfur level on $N_2O$ emissions can be seen by combining data from the EPA and CE-CERT testing of LEV vehicles, as shown in Table 8-4. As the data in Table 8-4 clearly show, LEV emissions of $N_2O$ are highly sensitive to sulfur level. On average, $N_2O$ emissions were five times higher with high-sulfur fuels than they were with low-sulfur fuels. Based on this, it is clear that the $N_2O$ emission rates used in MOVES2004 must be properly adjusted to account for fuel sulfur effects.

**Table 8-4**
**EPA and CE-CERT LEV and ULEV Data (g/mi)**

| Class | Vehicle | Program | Low Sulfur | High Sulfur |
|---|---|---|---|---|
| Passenger Cars | Camry | EPA | 0.014 | 0.032 |
| | Neon | CE-CERT | 0.004 | 0.046 |
| | LeSabre | CE-CERT | 0.004 | 0.013 |
| | Malibu | CE-CERT | 0.001 | 0.009 |
| | Corolla | CE-CERT | 0.008 | 0.032 |
| | average | | 0.006 | 0.026 |
| Light-Duty Trucks | Grand Caravan | EPA | 0.023 | 0.100 |
| | Windstar | EPA | 0.031 | 0.086 |
| | Safari | CE-CERT | 0.005 | 0.051 |
| | Caravan | CE-CERT | 0.010 | 0.058 |
| | Windstar | CE-CERT | 0.012 | 0.023 |
| | average | | 0.016 | 0.064 |

Separation of LEV I and LEV II and Tier 1 and Tier 2 Vehicles - The MOVES2004 document needs to be clarified to better document how the $N_2O$ emission rates were estimated. The current "Appendix A" to the report, which generally identifies which testing programs were utilized, is not adequate to determine which test programs and vehicles were used. For LEVs, the report should list the source (program) for the data, the fuel used (especially with respect to sulfur level), and the type of LEV vehicle (LEV I or LEV II, or ULEV I or ULEV II, etc.).

Our review leads us to suspect that all of the LEV test data used in developing the MOVES2005 $N_2O$ emission rates, and much of the test data that EPA did not use but will obtain prior to releasing the next version of MOVES, was from LEV I vehicles. As noted above, the LEV II and Tier 2 NOx standards are more stringent than those that apply to LEV I vehicles, and those more stringent standards are likely to lead to lower $N_2O$ emission rates. A similar impact may also be associated with the increase in the required emissions durability demonstration period from 100,000 miles to 120,000 miles.

While the best approach would be to collect $N_2O$ emissions data from LEV II and Tier 2 vehicles, if no such data are available the $N_2O$ emission rates for these vehicles should, at a minimum, be adjusted by the ratio of the applicable NOx emission standards after adjusting for the change in the durability demonstration period.

This approach is also supported by the fact that it appears that $N_2O$ to NOx ratios are fairly consistent from Tier 1 and LEV I vehicles. Table 8-5 shows $N_2O$/NOx ratios from several Tier 1 and LEV I vehicles tested in the CE-CERT and EPA test programs on both on both high- and low-sulfur fuels. The data show that a typical ratio on low-sulfur fuel is about 5–6%, but some vehicles are clearly higher, for example, the Camry and the Windstar. These two vehicles had NOx emissions that were in the range of the other vehicles, but the $N_2O$ emissions were a little higher than the others, resulting in higher ratios. The three Tier 1 vehicles are also around 5–6%. On higher sulfur fuel, the ratios are much higher than on lower sulfur fuel, indicating that $N_2O$ emissions are more sensitive to fuel sulfur levels than are NOx emissions.

**Table 8-5**
**$N_2O$/NOx Ratios in CE-CERT and EPA Data**

| Class | Vehicle | Year | Tech | $N_2O$/NOx ratios | |
|---|---|---|---|---|---|
| | | | | Low Sulfur | High Sulfur |
| Cars | Neon | 2000 | ULEV I | 0.074 | 0.258 |
| | LeSabre | 2000 | ULEV I | 0.059 | 0.210 |
| | Malibu | 2000 | LEV I | 0.016 | 0.127 |
| | Corolla | 2000 | LEV I | 0.054 | 0.154 |
| | Camry | unknown | LEV I | 0.255 | 0.390 |
| | Accord | 1996 | Tier 1 | 0.067 | 0.165 |
| LDTs | Windstar | 2001 | ULEV I | 0.308 | 0.232 |
| | Safari | 2001 | LEV I | 0.056 | 0.340 |
| | Caravan | 2001 | LEV I | 0.045 | 0.188 |
| | Tacoma | 1996 | Tier 1 | 0.054 | 0.159 |
| | Aerostar | 1996 | Tier 1 | 0.058 | 0.147 |

## 8.3 Critical Review of MOVES2004 $CH_4$ Emission Rates

There are more data from which to develop $CH_4$ emission rates than exist for developing $N_2O$ emission rates for vehicles certified to Tier 1 and less stringent standards. However, for LEVs, the EPA database includes data from only 17 vehicles. In reviewing the EPA database, we identified data from a CARB Surveillance program (CARB's 2S00C1 program) that appeared not to have been included in EPA's database. This database includes 42 passenger cars certified to either LEV (39 vehicles) or ULEV (3 vehicles) standards, as well as data from other vehicles certified to various, less stringent, emission standards.

Average FTP $CH_4$ emission rates for ULEV and LEV vehicles in this CARB data set are shown in Table 8-6, along with the MOVES2004 emission rates for LEVs. These data show that the $CH_4$ emission rates from the 39 LEV vehicles in the CARB database are about 34% less than the current MOVES2004 emission rate for this class of vehicle. The data also strongly suggest that the stringency of the NMOG standard, even at very low NMOG levels, has a significant effect on $CH_4$ emissions given the substantially lower $CH_4$ emission rates of the ULEVs.

**Table 8-6**
**Methane FTP Emission Rates (g/mi)**

| Source | Vehicle | Methane (g/mi) |
|---|---|---|
| CARB Surveillance data | ULEV | 0.0027 g/mi |
| | LEV | 0.0086 g/mi |
| MOVES2004 | LEV | 0.013 g/mi |

Clearly, the data from the 39 LEVs in the CARB test program should be combined with the data from 17 LEVs in the EPA database and the average $CH_4$ emission rate for LEVs used in MOVES2004 should be re-estimated.

The data from the CARB test program also suggest that MOVES2004 $CH_4$ emission rates should be related to the stringency of the NMOG or NMHC standard to which vehicles are certified. This is of particular importance given the multitude of such standards available in the LEV I, LEV II, and Tier 2 programs. To evaluate the need for such an adjustment we computed the ratio of $CH_4$ to total HC emissions for the passenger cars in the CARB database as a function of NMOG standard level. Results are shown in Table 8-7. The data in Table 8-7 indicate that a reasonable ratio to use for methane to THC is about 0.14.

**Table 8-7**
**Ratios of Methane to THC from ARB Data**

| HC FTP Standard | Sample Size | Methane/THC Ratio |
|---|---|---|
| 0.040 (ULEV) | 3 | 0.054 |
| 0.075 (LEV) | 39 | 0.155 |
| 0.125 (TLEV) | 19 | 0.136 |
| 0.250 (Tier 1) | 46 | 0.146 |

Another issue that EPA has failed to address is the impact of fuel sulfur level on $CH_4$ emissions, particularly those from vehicles certified to stringent NMOG/NMHC standards. As was recommended with respect to $N_2O$ emissions, EPA should not mix vehicles tested on high- and low-sulfur fuels, but should develop methane emission rates for use in MOVES at one sulfur level, and then develop sulfur correction factors for each technology group.

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# 9. REFERENCES


1. See http://www.epa.gov/otaq/models/ngm/moves2004synopsis.txt.

2. "MOVES2004 Energy and Emission Inputs," Draft Report, U.S. Environmental Protection Agency, EPA420-P-05-003, March 2005.

3. "Excess Emissions Identification Using the IM147 Test Produced with 'Revision 2 Max CO Standards', Sierra Research Report No. SR00-07-01, July, 2000.

4. F. Di Genova, et al., "Task Order No. 6 Speed Correction Factor Improvement – Vehicle Emissions Testing," prepared for the California Department of Transportation, Report No. SR02-07-02, July 8, 2002.

5. "Highway Capacity Manual, HCM 2000," Transportation Research Board, 2000.

6. E. Nam and R. Giannelli, "Fuel Consumption Modeling of Conventional and Advanced Technology Vehicles in the Physical Emission Rate Estimator (PERE) – Draft," U.S. Environmental Protection Agency, EPA420-P-05-001, February 2005.

7. "MOVES2004 Highway Vehicle Population and Activity Data," Draft Report, U.S. Environmental Protection Agency, EPA420-P-04-020, December 2004.

8. Pechan, E.H. & Associates, "Documentation for the Onroad National Emissions Inventory (NEI) For Base Years 1970-2002," prepared for EPA Office of Air Quality Planning and Standards, January 2004.

9. "MOVES Validation Results, Draft Report", EPA420-P-05-002, February 2005.

10. "Light Duty Automotive Technology and Fuel Economy Trends: 1975 through 2004," EPA420-R-04-001, April 2004.

11. "Update of Methane and Nitrous Oxide Emission Factors for On-Highway Vehicles," EPA420-P-04-016, November 2004.

12. "Emissions of Nitrous Oxide from Mobile Sources: Comments on the Draft Inventory of U.S. Greenhouse Gas Emissions and Sinks, 1990-1996", EPA420-R-98-009, U.S. EPA, August 1998.

13. "Energy and Emission Inputs", EPA420-P-05-003, March 2005.

14. "Nitrous Oxide Emission Factors for Mobile Sources," Michaels, Fulper, and Kolowich, U.S. EPA, presented at Air and Waste Management Association Emissions Inventory Conference, December 1998.

15. "The Impact of Gasoline Sulfur Levels on Vehicle $NH_3$ and $N_2O$ Emissions," Huai, Durbin, et al, College of Engineering, Center of Environmental Research and Technology (CE-CERT), University of California, Riverside.

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