ANALYZING THE UNCERTAINTY IN THE FUEL ECONOMY PREDICTION FOR THE EPA MOVES BINNING METHODOLOGY

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ABSTRACT

Developed by the U.S. Environmental Protection Agency (EPA), the Multi-scale mOnotor Vehicle Emission Simulator (MOVES) is used to estimate inventories and projections through 2050 at the county or national level for energy consumption, nitrous oxide (N\textsubscript{2}O), and methane (CH\textsubscript{4}) from highway vehicles. To simulate a large number of vehicles and fleets on numerous driving cycles, EPA developed a binning technique characterizing the energy rate for varying Vehicle Specific Power (VSP) under predefined vehicle speed ranges. The methodology is based upon the assumption that the vehicle behaves the same way for a predefined vehicle speed and power demand. When this has been validated for conventional vehicles, it has not been for advanced vehicle powertrains, including hybrid electric vehicles (HEVs) where the engine can be ON or OFF depending upon the battery State-of-Charge (SOC). The Powertrain System Analysis Toolkit (PSAT), a vehicle simulation software developed by Argonne National Laboratory, will be used to generate the MOVES bins as well as evaluate the errors. This paper will quantify and explain the fuel economy uncertainties introduced by the "average" vehicle in the representative source bins for several powertrain configurations, control strategies, and drive cycles defined in MOVES.

INTRODUCTION

EPA has been undertaking an effort to develop a new set of modeling tools for the estimation of energy consumption and emissions produced by on-road and off-road mobile sources. The product of this effort is the Multi-scale mOnotor Vehicle Emission Simulator, referred to as MOVES [1]. The primary goal of MOVES is to produce regional and national inventories of energy consumption and emissions based on the choices the user has for pre-aggregation of geographic and temporal resolution. In a way, MOVES can be used to estimate inventories and projections at the county level for fuel consumption and emissions such as nitrous oxide (N\textsubscript{2}O) and methane (CH\textsubscript{4}) from highway vehicles.

In order to predict county- or national-level fuel consumption, it is necessary to simulate a large number of vehicles or fleets on numerous driving cycles. MOVES is tentatively designed so that fuel consumption and emission rates would be derived from a road load-based criterion known as Vehicle Specific Power (VSP), which has been chosen as the primary activity-based causal variable in fuel consumption and emissions formation for modeling purposes. The operating conditions of a simulated vehicle are defined by a modal "binning" approach in which operational bins are defined on power demand (VSP) under predefined speed ranges. The fuel consumption and emission rates are determined from a look-up table of VSP bins, whose cells are occupied by various data sources statistically combined. The key assumption of binning methodology is that all vehicles can be characterized by speed and VSP.

The trip-based energy consumptions are determined using a statistical approach of "averaging out" for different operating modes. The "averaging out" modal approach is advantageous in many ways: (1) it is appropriate for larger modeling domains; (2) it allows any driving pattern to be modeled based on distribution of time spent in bins; and (3) it provides common energy consumption for all scales. However, there are some disadvantages to this approach: (1) it is limited in its ability to characterize futuristic vehicles as well as their comprehensive control strategies, and (2) it does not separate out differences in some engine operating conditions (e.g., engine speed).

The Powertrain System Analysis Toolkit (PSAT) [2], developed by Argonne using MATLAB/Simulink, is a vehicle modeling package used to simulate performance and fuel economy. It allows one to realistically estimate the wheel torque needed to achieve a desired speed by sending commands to different components, such as throttle position for the engine, displacement for the clutch, gear number for the transmission, or mechanical braking for the wheels. In this way, we can model a driver who follows a predefined speed cycle. Moreover, as components in PSAT react to powertrain controller commands, we can employ advanced component models, take into account transient effects (e.g., engine starting, clutch engagement/disengagement, or shifting), and develop realistic control strategies. Finally, by using test data measured at Argonne’s Advanced Powertrain
Research Facility, PSAT has been shown to predict the fuel economy of several hybrid vehicles within 5% for several driving cycles. PSAT is the primary vehicle simulation package used to support the U.S. Department of Energy (DOE) FreedomCAR research and development activities.

Several studies [3, 4] have demonstrated the validity of the binning approach for conventional vehicles. However, the degree of accuracy has not been fully demonstrated for advanced vehicles such as hybrid electric vehicles (HEVs). Thus, the magnitude of uncertainty has not yet been quantified. In this paper, PSAT will be used to compare the fuel economy of advanced vehicles obtained from the MOVES procedure (combinations of cycles) and PSAT (specific cycles). The uncertainties will be evaluated for several powertrain configurations, control strategies, and driving cycles. It is important to note that the uncertainty in emission prediction is omitted in this paper. Finally, only hot-start engine operations were simulated.

**VSP-BASED BINNING APPROACH METHODOLOGY**

EPA pursued an approach based on the binning of vehicle specific power on a second-by-second basis using pre-defined equations developed for characterizing VSP. VSP is generally defined as power per unit mass of the vehicle (kW/ton). The calculation of absolute power generally centers on the forces that a vehicle must overcome when operating on the road, including acceleration, the force of gravity due to positive road grade, tire rolling resistance, and aerodynamic drag. Normalizing this power by mass to calculate VSP allows for this metric to be estimated based only on the instantaneous speed of the vehicle and road grade. The equation for VSP is as follows:

\[
VSP = \nu \times (a \cdot (1 + \varepsilon) + g \cdot \text{grade} + g \cdot C_R) + \frac{\rho \cdot C_D \cdot A \cdot \nu^3}{2 \cdot m}
\]

Where:
- \( \nu \): Vehicle speed (m/s)
- \( a \): Vehicle acceleration (m/s²)
- \( \varepsilon \): Mass factor accounting for the rotational masses
  - grade: Road grade
- \( C_R \): Rolling resistance
- \( \rho \): Air density
- \( C_D \): Aerodynamic drag coefficient
- \( A \): Frontal area (m²)
- \( m \): Vehicle mass (tones)

The total activity of a group of vehicles or fleet is then subdivided into categories that differentiate energy consumptions, known as operating mode bins as shown in Figure 1.

The Mean Energy Rate represents the energy rate calculated by operating mode bins over the given cycles. As a consequence, it is crucial that driving cycles selected for the binning process cover a wide range of operating conditions. The larger the uncertainty on the Mean Energy Rate, the greater the final error.

It is important that the selection of driving cycles provides a wide speed spectrum with even distribution over 17 predefined operating modes so that each mean energy rate for corresponding VSP accurately represents the behavior of a group of vehicles at a given speed. For advanced technology vehicles, MOVES calibrates emission rates from three driving cycles: UDDS, HWFET, and LA92. The fuel economy for any driving cycle can be estimated based on the mean energy rates calculated from these three driving cycles.

**UNCERTAINTY EVALUATION PROCESS**

To evaluate the uncertainties, PSAT was used to generate MOVES fuel economies as well as the values to which they will be compared, as shown in Figure 2. PSAT is first used to generate the Binned Mean Energy Rate values based on the EPA MOVES Procedure (UDDS, HWFET, and LA92 cycles). Then, the cycle used for the simulation is analyzed to calculate the number of points we will have in each of the bins. Since MOVES calculates a second-by-second energy consumption, the number of points within each bin represents the total time spent for corresponding bin. Knowing the Mean Energy Rate and the number of points within each bin, the total energy consumption for each operating mode bin is calculated.
points within a bin, MOVES fuel consumption can be calculated.
For the same driving cycle, PSAT is then used to simulate the same vehicle. Both the MOVES and PSAT fuel consumption results can then be compared and the differences analyzed. In addition to the three driving cycles used as part of the MOVES binning process, three additional driving cycles will be considered to verify the uncertainties in fuel economy over diverse cycles: NEDC, Japan1015, and US06.

Figure 2. MOVES Fuel Consumption Estimation Process Using PSAT

PSAT CODE VALIDATION

In order to verify the accuracy of PSAT in fuel economy estimates, the validation is conducted on the conventional vehicle, which was modeled on the Ford Focus. The prediction for this vehicle is very good — 27.4 mpg simulated from PSAT versus 27 mpg from the EPA’s website [5] for city driving. The discrepancy in fuel economy is less than 2%. These results imply that PSAT can capture the fuel consumption behavior of conventional vehicles very accurately. Generally speaking, PSAT can predict the fuel economy and performance for advanced vehicles as well as conventional vehicles within a variance of 2% to 5%, depending on the data accuracy and the complexity of control algorithm.

However, the validation for MOVES has been done by EPA based on the comparison between fuel economy results derived from MOVES output and top-down estimates on a fleet-wide basis estimated by the Department of Transportation’s Federal Highway Administration (FHWA). The agreement between FHWA and MOVES fuel consumption is good, which would be characterized as “close,” giving approximately 10% discrepancy in fuel economy for a fleet of gasoline-based conventional vehicles [4].

Figure 3 shows that the fuel economy differences for the cycles used in the MOVES procedure are fairly small (4%), which is comparable to the analysis performed by EPA. As far as the new cycles are concerned, while the results with the NEDC and Japan1015 cycles also lead to small differences (4% and 3%, respectively), the main difference is seen with the US06 cycle at 20%.

Figure 4 shows the percent difference in fuel flow rate within a bin between MOVES and PSAT on the UDDS cycle. Because of the low values at low VSP bins, one should be careful when comparing percent differences. Indeed, the difference between 0.1 and 0.2 is insignificant compared to 10 and 20, even though they have the same percent difference. For this reason, actual fuel economy numbers and the percent differences are shown in Appendix 1 for comparison.

The numbers of points sampled within a bin are listed in red on the top of each bar. Approximately 91% (1248 out of 1372) of the total points fell into the bins with discrepancies of less than 5%. However, the largest discrepancy occurs in the bin in which the VSP is less than 6 kW/ton and vehicle speed is greater than 80 kph.
This specific discrepancy doesn’t significantly influence the total fuel economy number, because the number of points is only 30, which is a relatively small fraction (2%) of numbers compared to the total number of sampled points for the UDDS simulation.

UNCERTAINTIES INTRODUCED BY ADVANCED POWERTRAINS

In addition to the conventional vehicle, six powertrain configurations were selected to represent the currently available advanced vehicle technologies. The configurations selected have different hybridization degrees (e.g., low with starter-alternator, medium with power split and parallel, and high with plug-in HEV) and component technologies (e.g., engine vs. fuel cell):

- Starter-alternator parallel HEV
- Power split HEV
- Pre-transmission parallel HEV
- Plug-in parallel HEV
- Hydrogen fuel cell
- Fuel cell HEV

The gasoline-based internal combustion engine (ICE) conventional vehicle, modeled after a Ford Focus, is used as a reference vehicle. Moreover, all vehicle configurations used in this study are defined based on currently available vehicles in the market, except the plug-in parallel HEV case. For the plug-in parallel HEV vehicle, the components selected are the ones implemented in Argonne’s Mobile Advanced Automotive Testbed (MATT). MATT [6] is a rolling chassis used to evaluate component technology in a vehicle system context. The configuration selected is a pre-transmission parallel hybrid, very similar to the one used in the DaimlerChrysler Sprinter van [7].

As shown in Figure 5, the error on the US06 driving cycle is significantly higher than any other cycles for all the powertrain configurations. This discrepancy will be explained later in the paper.

FUEL CELL VEHICLE

In a fuel cell configuration, the fuel cell is directly linked to the electric machine and no battery is used in the system. Similarly to the conventional vehicle, the fuel cell powertrain has only one energy source. Because its behavior is very reproducible, the error introduced is minimal (less than 5%), as shown in Figure 5. This demonstrates that MOVES accurately captures the fuel economy behavior when a single power source is presented in the system. Although the fuel cell technology is currently too expensive to be commercially viable, the configuration was selected to suggest correlation between the error in the fuel economy prediction and the number of power sources in the system.

FUEL CELL HYBRID ELECTRIC VEHICLES

The fuel cell HEV (Series Fuel Cell HEV) incorporates a single gear reduction after the electric machine. Because of the fuel cell system’s high efficiency, the stored energy is not used as the primary power source. Indeed, when the efficiency of the fuel cell system is compared with that of the ICE, the fuel cell system is found to have high efficiency at low power. For a hybrid ICE, it is beneficial to use the battery at low and medium power levels and the ICE at high power levels — that is not, however, the case for fuel cell vehicles. Consequently, the default control strategy has been developed so that the main function of the battery is to store the regenerative braking energy from the wheel and return it to the system when the vehicle operates at low power demand (low vehicle speed). The battery also provides power during transient operations when the fuel cell is unable to meet driver demand. The logic used in the control strategy has been previously developed using a global optimization algorithm [8]. It is also important to note that the fuel cell system is never turned off. Instead, the system idles when no power is requested. The power rate fuel cell during idle is set to 0.3% of the fuel cell consumption at rated power.

Because of the control strategy logic, this powertrain configuration, despite having two energy sources, still has reproducible behavior due to the low battery usage. As one might expect, the accuracy of the fuel cell series remains very good compared to its conventional and fuel cell counterparts.

Figure 5. Fuel Economy Uncertainties between MOVES and PSAT for Various Drivetrain Configurations
STARTER-ALTERNATOR PARALLEL HYBRID ELECTRIC VEHICLES (PARALLEL HEV ISG)

In a starter-alternator parallel HEV configuration (Parallel HEV ISG), the electric machine is mounted primarily on the crankshaft between the engine and the transmission. The starter-alternator system provides the functions of an electric starter and an alternator. By using suitable advanced power electronic converter systems, it is possible for the electric machine to compensate the drivetrain oscillations to improve drive quality. However, because of the low electric machine power, its capabilities are limited. Using a validated model [9], the control strategy allows the engine to be tuned OFF during deceleration or after the vehicle comes to a complete stop. The role of the battery is then limited to regenerative braking and power assist at low vehicle speed. As the engine remains largely the primary energy source, the accuracy in the fuel economy prediction of the MOVES procedure is still very agreeable (less than 5% variation), as shown in Figure 5.

SPLIT HYBRID ELECTRIC VEHICLES

The split HEV powertrain is based on the validated model of the 2004 Toyota Prius [10]. Power split HEVs have much more sophisticated control strategies. The electric machine is used more frequently both for regenerative braking and power enhancement for acceleration purposes. Depending on the battery SOC, the engine can be ON or OFF, which increases the uncertainty in MOVES.

Figure 5 shows that the fuel economy prediction for the split HEV over six different cycles is within 8%, except for the US06 cycle. The error increased for all drive cycles compared to conventional vehicle.

The discrepancy in fuel economy prediction is the largest in the LA92 cycle. It is difficult to understand why significant discrepancy occurs on certain driving cycles while it doesn’t appear on other cycles, due to complexity of the control algorithm. However, as described earlier, the two important factors in hybrid control strategy are engine shut-off and regenerative braking. Even if regenerative braking has a significant impact on the overall fuel economy, the overall fuel consumption is mostly related to the engine behavior. Figure 6 demonstrates that the largest differences occur at low VSP (low power demand) due to the engine ON/OFF characteristics. Indeed, because the value of the mean energy rate for each bin is based on an average, if one value is based on an engine OFF state and the other one on an engine ON state, the range of the mean energy rate will be greater as the error.

The top graph in Figure 7 illustrates how fuel economy discrepancy is affected by number of engine ON events for each bin. The high correlation coefficient (0.86) indicates that the discrepancy in fuel economy is mostly correlated with number of engine ON events. It is interesting to note that the discrepancy in fuel economy can be significantly larger as the engine turns ON frequently in a short period of time. For example, the discrepancy in fuel economy becomes almost 100% as the number of engine ON events reaches 14 and the duration of engine ON time is less than 30%. On the contrary, the discrepancy decreases to within 5% when the engine is ON all the time.

PRE-TRANSMISSION PARALLEL HYBRID ELECTRIC VEHICLES

A pre-transmission parallel hybrid configuration was also selected for this study. From a structural point of view, the electric motor is located in between the torque converter and the gearbox, and the battery is directly
connected to the electric motor. However, the control logic for a pre-transmission parallel HEV configuration is relatively simpler than for a split HEV configuration. If the power required at the wheel is greater than a threshold, the engine will be turned ON. The threshold varies based on the battery SOC. The engine is then used close to its best efficiency curve, while the electric motor is charged or provides the additional power to meet the request.

MOVES performs better for a parallel HEV configuration than for a split HEV. The predictions are within 7%, as shown in Figure 5. This is most likely due to shut-off behavior of the engine in parallel HEV control logics, which are relatively less sensitive to operating conditions than in the split HEV counterpart.

One notices that the choice of SOC algorithm has a greater impact on the driving cycles, including, for the most part, lower average speeds and frequent stops, such as those seen in the NEDC driving cycle shown in Figure 5. For example, in the NEDC cycle, the fuel consumption was underpredicted by 7% for a parallel HEV, but only by 3% for a conventional vehicle on the NEDC cycle. The lower the average vehicle speed and the greater the number of vehicle stops, the larger the uncertainty.

PLUG-IN HYBRID ELECTRIC VEHICLES

The configuration selected for a plug-in hybrid electric vehicle (PHEV) is also a pre-transmission parallel hybrid. Table 1 shows the main characteristics of the simulated midsize vehicle. As mentioned earlier, the components selected are ones that have been implemented in Argonne’s MATT. The control strategy developed based on the optimization results will ultimately be implemented and tested on hardware.

The PHEV operates in two different modes depending on battery SOC:

- Charge-depleting mode: The electric energy is used as the primary mover. However, the engine will be turned ON when necessary (e.g., electric machine cannot provide sufficient power or engine can be operated at high efficiency area).
- Charge-sustaining Mode, similar to current HEVs.

<table>
<thead>
<tr>
<th>Table 1. Component Specification for PHEV</th>
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<tbody>
<tr>
<td>Component</td>
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<tr>
<td>Engine</td>
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<tr>
<td>Electric machine</td>
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<tr>
<td>Battery</td>
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<tr>
<td>Transmission</td>
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<td></td>
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<tr>
<td>Frontal Area</td>
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<tr>
<td>Final Drive Ratio</td>
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<td>Drag Coefficient</td>
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<tr>
<td>Rolling Resist.</td>
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<tr>
<td>Wheel radius</td>
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</tbody>
</table>

Originally, the initial and final SOCs were set to be 90% and 30% respectively, but this required a significant number of driving cycles to satisfy a target driving range for the electric only mode of PHEV operation. Based on the previous observation from conventional and fuel cell vehicles, we would expect that the uncertainty in fuel economy on charge-depleting mode for a PHEV is minimized, since a single power source (electric machine) is being used during operation.

For this reason, the charge-sustaining mode is only considered in this study. Instead of using the original 90% and 30% of initial and final SOC, the lower initial SOC (35%) is used to reduce the number of simulative iterations and reach directly to charge-sustaining mode. Figure 8 shows the behaviors of the engine and battery in the PHEV on the UDDS cycle.

As shown in Figure 5, the PHEV configuration has the greater discrepancies in fuel economy among the vehicles considered in this study. The variation in fuel economy changes from less than 1% to 27% as driving conditions change.

Figure 9 explains why the discrepancy increases up to 27% on the Japan1015 cycle for PHEV configuration. The deviation in mean energy rate calculation for PSAT is relatively very small for all bins. On the contrary, the deviation is higher in MOVES, which increases the fuel economy uncertainty. In addition, there are no points captured in Bin 33, Bin 35, and Bin 36 by PSAT. The reason for this is because the maximum power and speed required by the PHEV in the Japan1015 driving cycle is relatively smaller than the high end of pre-defined bins, thus, no points fell into those bins.
It is important to note that battery SOC balance undertakes the most important role in hybrid control strategy along with regenerate braking. While all the previous cases have been simulated with corrected SOC, it is not often the case in real-world driving conditions.

As shown in Figure 10, the MOVES method predicts the fuel economy for a parallel HEV with SOC correction within 3%, compared to a 1% discrepancy for the same vehicle without SOC correction. In the control strategy used, the vehicle has a tendency to deplete the battery. As a consequence, the SOC correction forces the engine to be ON more frequently to keep up the SOC target in the control strategy algorithm.

We demonstrated that significant discrepancies were found in the US06 cycle for all the drivetrain configurations. Figure 11 shows the difference in fuel flow rate between MOVES and PSAT within each bin over the US06 cycle.

The significant differences occur because the range of speed spectrum of the MOVES procedure, which combines the UDDS, HWFET, and LA92 cycles, could not cover the harder accelerations and higher speeds of the US06 cycle. Figure 12 shows the speed distribution in percent for the MOVES procedure and US06 cycle. It is obvious that the half-speed spectrum of the US06 cycle (red) is outside the spectrum of the MOVES procedure (blue).

In order to overcome the “out-of-range” problem of the original binning methodology, two approaches were considered to achieve a better representation for VSP binning methodology:

1. The higher driving cycle should be chosen to represent the wider spectrum of speed trace (options 2 and 3).
2. The bins for the harder accelerations and higher speeds are extended up to 30 VSP. In this study, two more bins were added after Bin 36 by an increment of 6 kW/ton, where the speed is greater than 80 kph (options 4, 5 and 6). The list of the combinations examined for this study is in Table 2.

The uncertainty study was performed in response to a change in driving cycle in the MOVES procedure. Figure 13 shows fuel economy variation is minimized to 7% when the MOVES procedure incorporates the UDDS, HWFET, and US06 cycles.

Table 2. List of Options for MOVES Procedure

<table>
<thead>
<tr>
<th>Options</th>
<th>Descriptions</th>
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<tbody>
<tr>
<td>1</td>
<td>UDDS + HWFET + LA92</td>
</tr>
<tr>
<td>2</td>
<td>UDDS + HWFET + US06</td>
</tr>
<tr>
<td>3</td>
<td>UDDS + HWFET + LA92 + US06</td>
</tr>
<tr>
<td>4</td>
<td>UDDS + HWFET + LA92 + US06 + Extended Bins</td>
</tr>
<tr>
<td>5</td>
<td>UDDS + HWFET + LA92 + Extended Bins</td>
</tr>
<tr>
<td>6</td>
<td>UDDS + HWFET + US06 + Extended Bins</td>
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</table>

Figure 14 also illustrates the validation of the MOVES procedure with two extra bins:

- Bin 37: Vehicle Speed $\geq 80$ [kph] and $18 \leq VSP \leq 24$ [kW/ton]
- Bin 38: Vehicle Speed $\geq 80$ [kph] and $24 \leq VSP \leq 30$ [kW/ton]

Extra bins help to decrease the uncertainty in fuel economy predictions for the US06 driving cycle. The percent difference in the US06 driving cycle decreases by 7% when using extra bins with the original MOVES procedure (UDDS, HWFET, and LA92). The next version of MOVES (2006) is expected to increase the number of high-VSP bins.
Overall, the combination of the UDDS, HWFET, LA92, and US06 driving cycles with two extra bins predicts the most accurate fuel economy estimates for the given driving cycles. The discrepancy is less than 4% for driving cycles including low-to-medium speed ranges, and 7% for high-speed ranges, like US06. The MOVES procedure with extended driving cycles and bins is likely to capture representative “real-world” driving patterns as well. The speeds are evenly distributed up to 112 kph, where 35% of speeds in the US06 driving cycle are distributed.

CONCLUSION

The MOVES VSP binning procedure has been integrated into PSAT to validate the accuracy of the binning methodology. The comparison results demonstrated that:

- The MOVES procedure predicts the fuel economy very well for single-power-source vehicles, such as conventional and fuel cell vehicles with an uncertainty lower than 5%.
- The percent differences in fuel economy estimates increase with the hybridization of HEVs. The maximum error can be viewed for PHEVs (20% on NEDC).
- The discrepancies in fuel economy on HEVs are mostly due to non-repeatable engine ON/OFF behavior.
- The current MOVES procedure cannot accurately predict fuel economy for the simulation run on the driving cycle demanding high acceleration and high speed (e.g., US06).
- The combination of the UDDS, HWFET, LA92, and US06 cycles with two extra bins for the MOVES procedure can be used to minimize the “out-of-range” problem in the US06 cycle.

The VSP binning procedure is very powerful and extremely well-adapted to the purpose of MOVES, as it is independent of the driving cycle and allows users to quickly analyze regional and national averages within an acceptable uncertainty range. While using a detailed approach such as PSAT is feasible for specific vehicles, it would not be applicable for MOVES because of the very large range of vehicles and timeframes considered. Overall, this study demonstrated that the uncertainties introduced by the current procedure were acceptable to fulfill the purpose of the simulation tool, aimed at estimating inventories and projections through 2050 at the county level for energy consumption, nitrous oxide (N2O), and methane (CH4) from highway vehicles.

ACKNOWLEDGEMENTS

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### APPENDIX 1. Fuel Economy Comparison between PSAT and MOVES Procedures

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<td>Compact Conventional (Ford Focus)</td>
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