Energy Consumption and Emission Modeling of Individual Vehicles Using MOVES-Matrix

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ABSTRACT

This study demonstrates an approach to modeling individual vehicle second-by-second fuel consumption and emissions based on vehicle operations. The approach uses MOVES-Matrix, a high-performance vehicle emission modeling system consisting of a multi-dimensional array of vehicle emission rates (pulled directly from the US Environmental Protection Agency's MOVES emissions model) that can be quickly queried by other models to generate an applicable emissions rate for any specified on-road fleet and operating conditions. For this project, the research team developed a spreadsheet-based MOVES-Matrix Calculator (MMC) to simplify connecting vehicle activity data with multidimensional emission rates from MOVES-Matrix. This paper provides a "walk through" of the calculation procedures, from basic vehicle information and driving cycles to second-by-second emission rates. The individual vehicle emission modeling framework is incorporated into *Commute Warrior*®, a travel survey application based on an Android® smartphone, to provide real-time fuel consumption and emission rate estimates from concurrently obtained GPS-based speed data.

Keywords: MOVES, MOVES-Matrix, Individual Vehicle, Real-Time Emission Modeling

INTRODUCTION

Vehicle fuel consumption and emissions are a function of vehicle and engine characteristics, environmental conditions, and on-road operating conditions that influence engine load and work. Second-by-second vehicle operating data obtained from a variety of sources (e.g. smartphone tracking, machine vision, on-board monitoring, traffic simulations, etc.) can be coupled with second-by-second emission rates for use in travel decision making. This allows comparisons of fuel consumption and emissions impacts across alternative modes, across alternative travel routes, and for different traffic conditions likely to arise during a trip. Smartphone apps and in-vehicle monitoring systems can also be modified to provide travelers with real-time fuel consumption and emissions predictions, once emission rate algorithms are tied to monitored on-road operating condition (speed-acceleration) data.

This paper provides an overview of the energy and emissions modeling approach adopted for one of five ARPA-E TRANSNET projects that will implement high-resolution regional transportation simulation and influence consumers to reduce energy consumption through changes in travel behavior (*1*). The Georgia Institute of Technology is working with Southern Methodist University, AirSage®, and supporting partners, to develop advanced regional transportation simulation modeling systems to better predict energy consumption of transportation alternatives. In this project, the research team will implement a control architecture designed to monitor individual vehicle activity, estimate energy and emissions in real time, and encourage travelers to minimize surface transportation energy consumption in their travel decision making.

The energy and emission rate modeling approach presented in this paper employs the modal emissions modeling framework developed by the U.S. Environmental Protection Agency (U.S. EPA) in their Motor Vehicle Emission Simulator (MOVES). This study incorporates MOVES-Matrix (*2*), a high-performance emission modeling system, which consists of a multi-dimensional array of vehicle emission rates generated through iterative runs of the MOVES model. Because MOVES-Matrix includes the component emission rates for any vehicle source type, model year, and applicable modeling parameters available within MOVES, the tool allows users to calculate second-by-second vehicle emissions rates for any vehicle or fleet of vehicles that can be modeled in the current regulatory model.

The matrix of emissions rates can be quickly queried by other models to generate applicable energy use and emissions rates for a specified fleet under all common on-road operating conditions. For the ARPA-E project, the research team developed a new MOVES-Matrix interface that allows users to specify a vehicle make, model, and model year (using drop-down menus), and identifies the MOVES vehicle source type given the selections. The server responds to the query by sending the corresponding MOVES-Matrix energy and emissions modeling parameters and an applicable sub-matrix of energy and emission rates to the computational unit (vehicle computer or smartphone) for use in second-by-second emissions and energy consumption modeling for the vehicle. The research team constructed the MOVES-Matrix Calculator (MMC) spreadsheet to demonstrate the approach, refine the programming, and refine the calculation procedures that use basic vehicle information and any input driving cycle (second-by-second speed/acceleration profile) to generate second-by-second fuel consumption and emission rates. Other modal fuel consumption and emissions modeling tools have also been developed, such as PERE (*3*), CMEM (*4*), and conventional diesel bus fuel models such as those developed by Feng, et al., (2007) (*5*) and Wang and Rakha (2016) (*6*). While these alterative modeling tools also enable users to use second-by-second vehicle operation data as activity input, they all operate off-line and require users to prepare and import model input files. The research team has incorporated the more straightforward MOVES methods directly into energy and emissions calculations in the *Commute Warrior*® Android® smartphone activity monitoring and travel survey application, which allows the app to quickly predict real-time fuel consumption and emission rates using the second-by-second speed data concurrently obtained by the smartphone GPS module. Considering the popularity and widespread use of smartphones, *Commute Warrior*® should be a cost-effective tool for collecting large amounts of travel behavior and vehicle operations data for fuel and emission modeling. The team is currently developing the visual interface pages for the app to display the calculated energy and emissions for use in the project.

MOVES ALGORITHMS

In MOVES (*7*), driving cycles (speed-acceleration activity) can be decomposed into operating mode bins and modeled as a function of time spent operating in each bin. This innovative design allows MOVES to provide common emission rates for all modeling scales (macroscale, mesoscale, and microscale). The "binning" approach in MOVES connects emission rates and vehicle activity in each operating mode bin. MOVES includes an emission database with base emission rates for each pollutant in each operating mode bin, by vehicle regulatory class, model year from 1960 and project to 2050, and at vehicle age, covering almost all fleet types in the United States. MOVES is capable predicting emissions using default driving cycles embedded in the model, but also allows users to incorporate local vehicle operation by directly importing driving cycles or operating mode distributions directly. As indicated above, additional data inputs are required, including traffic volumes, vehicle type and fleet age distributions, meteorology, calendar year of analysis, fuel specifications, and inspection and maintenance program elements.

In applying the MOVES algorithms to individual vehicles to predict fuel consumption and emissions, the applicable algorithms in MOVES must be employed for Vehicle Specific Power (VSP, for light-duty vehicles) and Scaled Tractive Power (STP, for heavy-duty vehicles) calculation, and then the applicable emission rates must be applied for the VSP or STP condition given environmental conditions, fuel specification, and other parameters. VSP and STP are a function of vehicle mass, dynamics parameters, speed, acceleration, and gravitational acceleration. Instantaneous VSP and STP are calculated as (*8*):

$$VSP = \left(\frac{A}{M}\right)v + \left(\frac{B}{M}\right)v^2 + \left(\frac{C}{M}\right)v^3 + \left(\frac{m}{M}\right)(acc + g * \sin\theta)v \quad (1)$$

$$STP = \left(\frac{A}{M}\right)v + \left(\frac{B}{M}\right)v^2 + \left(\frac{C}{M}\right)v^3 + \left(\frac{m}{M}\right)(acc + g * \sin\theta)v \quad (2)$$

Where:

$VSP = vehicle\ specific\ power\ (\frac{kW}{tonne}, power\ to\ weight\ ratio),$

$STP = scaled\ tractive\ power\ (kW/tonne)$

$v = second - by - second\ velocity, m/sec$

$acc = second - by - second\ acceleration, m/sec^2$

$g = graviational\ acceleration\ (9.81\ m/sec^2)$

$\theta = road\ grade\ (radians\ or\ degrees, as\ needed\ in\ sin\ calculation\ algorithms)$

$m = vehicle\ mass\ (tonnes)$
$A = rolling\ resistance\ (kW - sec/m)$
$B = rotating\ resistance\ (kW - sec^2/m^2)$
$C = aeodynamic\ drag\ (kW - sec^3/m^3)$
$M = fixed\ mass\ factor\ for\ the\ source\ type\ (tonnes)$.

Readers will note that the functional form of the VSP and STP equations are exactly the same. For all practical purposes, the modeling approaches for light-duty and heavy-duty vehicles are the same. However, the m/M ratio is assumed to be 1.0 for light-duty vehicles, whereas the M in the heavy-duty vehicles formula is essentially a constant power scaling factor, which is approximately the average running weight for all heavy-duty vehicles. The factor is used to scale STP ranges to within the same range as VSP (*9*). Hence, in addition to using significantly different model coefficients for A, B, and C, the STP calculation also uses different (user-modifiable) heavy-duty vehicle values for vehicle mass and fixed mass factor.

VSP and STP bins are established for three types of operations: braking, idle, and cruise-acceleration. Bins for cruise-acceleration are further separated into three average speed groups (0-25 mph, 25-50 mph, 50+ mph), and then into VSP ranges within each average speed group. Higher VSP and STP values within specific operating speed ranges are linked with higher fuel consumption, CO_2 emission rates, and criteria pollutant emission rates. Figure 1 below presents an example of the MOVES CO_2 emission rates (equivalent to energy consumption) for model year (MY) 2016 passenger truck in each operating mode bin (defined as speed and VSP ranges in MOVES model). High speeds, moderate accelerations at high speed, and hard accelerations at moderate or high speed, push on-road activity into higher VSP bins, which are assigned higher fuel consumption and emission rates in the MOVES model.

FIGURE 1 Example CO_2 Emission Rates by VSP Bin for Passenger Trucks (MY 2016).

In implementing a second-by-second emission prediction system, each parameter in Equation (1) and (2) must be made available to the calculation algorithms. Given a second-by-second operating mode distinction (braking, idle, and acceleration-cruise), an average speed, and an applicable VSP value, the appropriate emission rate for the vehicle source type can be extracted from MOVES-Matrix. For selecting the operating mode and calculating VSP in real-time, second-by-second speed data can be obtained from the vehicle's onboard diagnostics (OBD) system or from real-time GPS data for speed and acceleration inputs.

MOVES-MATRIX

In the Georgia Tech ARPA-E project, the goal is to simultaneously estimate second-by-second fuel consumption and emission rates using data from thousands of vehicles covering all kinds of vehicles types. MOVES outputs average energy consumption and emission results, rather than second-by-second rates; but, the MOVES model does contain instantaneous rates embedded in the model. Because emissions are a complex function of many locally-dependent variables, and because MOVES integrates aggregation functions for emission estimation for states and counties, the interface is complex and requires numerous inputs to properly characterize a specific emission scenario needed by a user. Significant labor is required to prepare MOVES input files. In addition, running MOVES is time-consuming, because emission calculations always begin with base emission rates, and for each run, the data are internally adjusted for such aspects as temperature, humidity, fuel property, etc. This makes it difficult to use MOVES to assess large-scale transportation networks that experience dynamic changes in on-road fleets and operating conditions. The research team developed the MOVES-Matrix modeling approach to take advantage of the operating mode bin approach employed inside the MOVES model, and the fact that the model allows users to specify the fleet composition down to a single vehicle source type. In essence, the team could run the MOVES model for any specific fleet and set of operating conditions, generating on-road emissions for a uniform fleet (i.e., composed completely of one type and age of vehicle).

MOVES-Matrix is composed of the outputs from a tremendous number of MOVES model runs. The basic process is to run MOVES across all variables that affect emission output, where each iteration yields a pollutant emission rate for a uniform source type (all vehicles represented in the run are a specific vehicle source type), a uniform model year (age group), for a specific vehicle fuel type (gasoline, diesel, CNG, etc.), a specific on-road operating condition (a single on-road VSP/STP operating mode bin), a single calendar year, applicable regional regulatory parameters (fuel properties, vehicle inspection and maintenance (I/M) program characteristics), and specific temperature and humidity condition. The MOVES-Matrix runs for each region reflects the regional I/M program and fuel specification by month. The one drawback is that when a region wants to assess a scenario in which the fuel specifications or I/M program change from the current regional values, a new set of MOVES-Matrix runs (146,853 model runs) need to be processed for the analysis. Table 1 presents the iteration parameters employed in MOVES-matrix.

TABLE 1 MOVES-Matrix Iteration Parameters

MOVES starts with a set of baseline emission rates, and these baseline emission rates are adjusted with temperature, humidity, air conditioning use, fuel property, and inspection and maintenance strategy during each run before they are connected to activity data. MOVES-Matrix stores adjusted emission rates for all scenarios (i.e., surrounding environmental information that is unique for each single MOVES run, including the calendar year, fuel month, temperature, humidity, and inspection/maintenance strategy), and for the scenario of interest. It filters the pre-run emission rates for the specific scenario, rather than doing adjustment calculations. There are no code modifications, no correction factors, and no approximations involved, which ensures that the emission results obtained from MOVES-Matrix are exactly the same with from MOVES model, and processing speed is over 200 times faster than MOVES. MOVES-Matrix is open source and collaborative. Python, Java, Perl, or any other regular language scripts can be used to link MOVES-Matrix emission rates with travel demand models, traffic simulation, monitored data, and dispersion models. More information on setup, implementation and application of MOVES-Matrix can be found in Guensler et al. (2016a) (*2*).

MOVES-MATRIX CALCULATOR (MMC)

MOVES-Matrix Calculator (MMC) is a spreadsheet tool created by the Georgia Tech team that provides second-by-second MOVES fuel consumption and emissions for an individual vehicle using MOVES-Matrix emission rates as a function of the vehicle (make/model/model year), second-by-second on-road activity, and meteorology (Guensler et al., 2016b) (*10*). In the MMC, the emission rates for the vehicle of interest are pre-loaded from MOVES-Matrix into an emission rate lookup matrix. The applicable MOVES VSP parameters for the vehicle (A, B, C, D, M, and m), given the MOVES vehicle source type, are also loaded into the MMC. These parameters are available for almost all vehicle makes, models, and model years normally seen on road. The MMC uses the VSP parameters, the VSP equation, and second-by-second speed and acceleration to calculate VSP, and then select the applicable emission rate for each second of operation from the emission rate matrix. The MMC algorithm design is shown in Figure 2 below.

FIGURE 2 MMC Algorithm Design.

When a vehicle make, model, and model year are chosen by the user, the vehicle source type in MOVES is automatically identified from a lookup table, and the applicable VSP vehicle parameters are identified for VSP calculations. To facilitate source type identification, the research team prepared a look-up table with 6,000+ rows for vehicle make, model, model year, vehicle regulatory class, fuel technology, that are linked to corresponding MOVES vehicle source type. The lookup also contains all of the modeling parameters used in VSP/STP calculations. Information for individual vehicles is easily converted to corresponding vehicle source type in MOVES for emission rate connection if the make, model, and model year are obtained from a registration database. For the vehicle make, model, and model year of interest, the subset of corresponding emission rates for the vehicle source type (associated with vehicle make and model), fuel type, model year, is extracted from MOVES-Matrix for all operating mode bins, temperatures, and humidity combinations.

After a vehicle speed trace is imported into the MMC, second-by-second VSP is calculated as a function of source-type dynamics parameters, speed, acceleration, and road grade. The operating mode bin for each second is allocated according to VSP and speed values. The second-by-second fuel and emission rate can be assigned by extracting the emission rate of corresponding operating mode bin, for the temperature and humidity specified. The summary of fuel consumption, emissions, and operating speed for each second of operation is shown in the resulting MMC output. In this way, users can obtain exactly the same fuel consumption and emission results as calculated from MOVES, the USEPA-approved regulatory emissions model. To illustrate the use of the MMC approach and calculation methodology, results for eight make, model, and model year vehicles are presented from a demonstration MMC spreadsheet:

- 1999 Ford Explorer (conventional gasoline engine);
- 2004 Honda Pilot (conventional gasoline engine);
- 2011 Hyundai Sonata (conventional gasoline engine);
- 2016 Subaru Forester (conventional gasoline engine);
- 2016 Toyota Prius (gasoline hybrid engine);
- 2016 Nissan Leaf (electricity engine);
- 2016 Ram 2500 (conventional gasoline engine);
- 2016 Ford Explorer (conventional gasoline engine)

The vehicle parameters of the eight vehicle models are presented in Table 2.

TABLE 2 MOVES Vehicle Dynamics Parameters for the Eight Vehicles

As can be seen in the table, many vehicles belong to the same MOVES source type, and therefore use the same set of VSP parameters. Thus, uniform MOVES emission rates are assigned to multiple vehicle models. For example, the 2011 Subaru Forester and the 2011 Hyundai Sonata are both assigned the same emission rates by MOVES for the same operating conditions. Yet, the actual fuel economy and emissions for these vehicles are likely different and their actual on-road engine performance likely varies somewhat across operating modes (as a function of vehicle drivetrain design). While this is an inherent limitation in using the MOVES model, the emission rates are federally-approved and represent the most reasonable rates currently available for a diverse on-road fleet. Vehicle make, model, and model year parameters could be used to better reflect on-road vehicle performance and emissions (for example, by adjusting scaling emission rates by highway fuel economy rating), but doing so would require making additional modeling assumptions and assertions that would also need to be verified to ensure than new and additional modeling biases are not introduced into the modeling regime. The authors will leave the further disaggregation of the MOVES model to USEPA model development teams. The important element in the application of the MOVES approach is that even though base emission rates between specific makes and models are likely to be different, the model provides the best approach to assessing how these vehicles are likely to respond to changes in onroad operating conditions. Because the research application will predict relative changes in emissions, and will not be used to compare baseline emissions across vehicles, the team is comfortable with the application of the MOVES emission rates.

To illustrate the differences in emissions calculations by vehicle age, Figure 3 presents the second by second fuel rate and CO_2 emission rate for a 1999 Ford Explorer and 2016 Ford Explorer operating on the FTP/EPA75 driving cycle (calendar year 2016, Temperature: 60°F, Humidity: 45%). The spreadsheet calculations are very fast and the data in the spreadsheet is relatively small. Hence, the straightforward algorithms outlined earlier can be easily incorporated in smartphone application for real-time calculation.

FIGURE 3 a) FTP/EPA75 Second-by-Second Driving Cycle, b) Fuel Consumption Rate, and c) CO2 Emission Rate*.

MMC Calculations for Individual Vehicles

The MOVES algorithms in the MMC and the base emission rate data were integrated into the *Commute Warrior®*, an Android® travel survey application, to facilitate real-time calculation of fuel consumption and emissions. The local ambient meteorology, including temperature and humidity, can be obtained from a local meteorological broadcast. After installing the *Commute Warrior* app, the user is asked to input their vehicle make, model, model year, and fuel type (usually there is no need to ask, as only one fuel type is available). The app identifies the corresponding MOVES vehicle source type ID using the vehicle model-regulatory class-source type look-up table described earlier. The MOVES vehicle dynamics parameters for VSP calculation (A, B, C, D, M, and m) as well as fuel consumption and emission rates of the vehicle source type are then transmitted to the user's smartphone. When the user is traveling, the GPS unit in the smartphone monitors second-by-second vehicle position and speed. Second-by-second VSP is then calculated concurrently using speed, acceleration, vehicle dynamics parameters, weight, and road grade (if available). The MOVES operating mode bin for each second is then allocated to that second of operation using the calculated VSP and speed data.

As discussed earlier, the MOVES model treats fuel consumption and emission rates for each single vehicle type as a function of multiple variables, including temperature, humidity, model year, calendar year, fuel supply, I/M strategy, and operating mode bin.

The total size of the MOVES-Matrix database to cover all possible source types and conditions exceeds 10 GB. Hence, the research team uses the identified vehicle source type by the user to download only a small portion of the MOVES-Matrix table to the smart phone from the server (about 4 Mb). A limited number of pollutant types are downloaded (criteria pollutants and CO_2), the summer and winter meteorology ranges are limited (e.g. emission rates at 20ºF are not present during the summer), and matrix tables consider summer, transition, and winter fuels. Hence, once the VSP bin for the second of operation is identified, the emission rate lookup from the matrix for the current temperature and humidity is all that is needed.

CASE STUDY (HOME-TO-WORK TRIPS)

To evaluate the second-by-second modeling capabilities for emissions and fuel consumption associated with the fleet purchase alternatives, the team collected second-by-second home-to-work data for the case study household using *Commute Warrior*. Table 3 summarizes the one-week analytical data set use in this case study.

TABLE 3 Summary of Case Study Data Set

The GPS data underwent a quality assurance/quality check (QA/QC) and post processing before being used in the analyses. The researchers applied a spline algorithm to fill in small data gaps (<4 seconds). Also, speed values are filtered to eliminate low-validity GPS speeds (typically at low speeds and in urban street canyons) with location-inferred speed (*11*). The Kalman filtering and spline process will be incorporated into *Commute Warrior* before the traces go to fuel consumption and emissions calculation process, but is not currently implemented. The trip map and speed versus time trace of one trip are shown in Figure 4. The user is able to playback the trip route and shows the speed at each point along the trip.

FIGURE 4 Home-to-Work Monitored Trip and Speed Trace.

Comparative Analysis

Consider a case where a user currently owns a 1999 Ford Explorer, and is considering purchasing a 2016 Ford Explorer. These two vehicle models are then used in this case study for comparative analysis. Figure 5 shows the speed traces as well as calculated second-by-second fuel consumption rate, CO_2 emissions, and $PM_{2.5}$ emissions of both the 1999 and 2016 Ford Explorer models. From the figure, Ford Explorer fuel economy has been improved somewhat from the 1999 to 2016 model, reducing CO_2 emissions. Most of criteria pollutant emissions (e.g., NOx, CO, PM) have been reduced by more than 90% due to changes vehicle fuel economy and federal emission standards.

FIGURE 5 Second-by-Second Speed, Fuel Consumption and Emission Rate*.

For this case study, five morning period commute trips were selected for analysis. The total duration of the five trips is 67.7 minutes. There were 60.95 minutes of second-by-second data recorded, and 6.75 minutes of data were omitted due to phone signal loss. To calculate the total emissions and energy consumption, the average emission rate in grams/second is first calculated from the recorded data, assuming the recorded data and derived operating mode distribution represent the overall trip. The scaled total emissions are then obtained with the multiplication of emission rate with total trips time (67.7 minutes).

Figure 6 illustrates the operation mode bin distributions and emissions share of each operating mode bin (defined in Figure 1) summarized from home-to-work trips using the 1999 Ford Explorer model. As shown in Figure 6, since the trips happened in local roads, very few operating points fell into in the high level of VSP bins (>18 KWh/ton) and high-speed bins (>50mph). However, some of the operations represented high engine load. For example, activity in operating mode bins 16 and 30, which represent VSP level greater than 30 KW/tonne, occurred less than 4% of the total operating time, but contributed 16% of fuel consumption. This activity also contributed greatly to pollutant emissions, including 59.5% of $PM_{2.5}$ emissions, 37.6% of CO emissions, as well as 17.8% of NOx emissions. This indicates the significant potential of fuel saving and emission reductions benefit from eco-driving training. For example, parallel research indicates that driver training in transit fleets can reduce fuel consumption by about 4%, by reducing high speeds and hard acceleration that is associated with high STP (*12*).

FIGURE 6 Operating Time Percentage and Emissions for Each Operating Mode Bin for the 1999 Ford Explorer*.

Table 4 shows the total energy consumption and emissions of the five home-to-work trips estimated based on eight vehicles models. The table clearly identifies a deficiency of directly applying MOVES emission rates to individual vehicles for fuel and emission modeling. MOVES treats regular electric and hybrid electric vehicles the same as conventional gasoline or diesel vehicles. For example, fuel and emission rates of 2016 Toyota Prius and 2016 Subaru Forester are the same, regardless of the higher efficiency of the hybrid drivetrain in the Prius model. Plus, the performance of hybrid vehicles across driving cycles is different from conventional vehicles (regenerative braking, coast, battery charge operations, etc.). While the emission rate of 2016 Nissan Leaf is set to 0, the fuel economy is listed as the same level of other 2016 regular passenger cars even though the energy consumption is typically much lower when fueled from the electric grid. The *Fuel and Emission Calculator* (FEC) developed by Georgia Tech and Oak Ridge National Laboratory incorporates algorithms to better model hybrid and electric vehicle emissions (*13*, *14*), and the battery charge and load support algorithm will be applied for modeling of new technology.

TABLE 4 Comparative Total Energy Consumption (gallons) and Emissions (grams) of Home-to-Work Trips Based on Eight Vehicles Models

CONCLUSION

This study introduced a MOVES method for individual vehicle modeling to predict second-by-second fuel consumption and emissions. This study used emission rate from MOVES-Matrix, a high-performance emission modeling system that uses 90 billion emission rates from 146,853 MOVES runs. The analyses presented in this paper demonstrate that MOVES-Matrix can the same emissions computations 200-times faster than using the MOVES model and that the generated results are exactly the same. The team incorporated the emissions modeling approach in *Commute Warrior*®, an Android® travel survey application, to predict real-time fuel consumption and emissions given second-by-second speed data concurrently collected by the smartphone GPS.

Embedding the MOVES-Matrix modeling approach into the Commute Warrior app facilitates energy and emission modeling in real time for monitored vehicle activity. The system also allows researchers to directly assess strategies designed to change individual travel behavior to increase efficiency, and to evaluate the potential impacts of major transportation design and operation strategies. The fast computational capability developed in this study supports the linkage between emission modeling technology and large-scale simulation modeling that involves massive numbers of vehicles in real-time. Energy and emission analysis tools coupled with simulation in the Atlanta ARPA-E project will support short-time-prediction, and feedback to travelers to support more efficient decision making. Users will be able to track changes in fuel consumption, carbon footprint, and emissions, and playback vehicle speed and fuel consumption rates along trip routes, and generate trip summary reports by time period or trip purpose.

However, it is important to note the limitations of individual vehicle fuel and emission modeling using the MOVES method, considering the challenge from embedded vehicle classification mix as well as the lack of refined engine load modeling for hybrid and electric vehicles. For the time being, MOVES emission rates represent aggregated average of certain vehicle class group rather than specific vehicle models. While the absolute fuel consumption values calculated through MOVES may not reflect the relative fuel efficiency across specific vehicle models within a source type, the relative energy benefits associated with changes in onroad operating conditions can still be modeled. For example, changes in onroad operating conditions associated with changes in departure time, commute mode, commute route, and improved driving habits (eco-driving) can be modeled. Future models will need to integrate more refined baseline emissions for specific subfleets and integrate enhancements to address subfleet-specific impacts of onroad operations on engine load. In addition, the algorithms from the *Fuel and Emission Calculator* (FEC) need to be incorporated for alternative technology vehicles, since the FEC performs better for hybrid and electric vehicle emissions, as battery charge and load support mechanisms are more fully represented.

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LIST OF TABLES

LIST OF FIGURES

TABLE 1 MOVES-Matrix Iteration Parameters

Model Parameter	Variable Range	Granularity	Number of Values
Calendar Year	2010 - 2024	1 year	15
	2025 - 2050	5 years	6
Temperature	0 - 110°F	1°F	111
Humidity	0 - 100%	5%	21
Fuel Specification	Three Seasons	Summer, Winter, Transition	3
Regional Input Combinations			146,853
All Vehicle Source Types and Model Years included			

TABLE 2 MOVES Vehicle Dynamics Parameters for the Eight Vehicles

Vehicle Model	**Model Year**	**MOVES Source Type**	**A**	**B**	**C**	**M**	**m**
Ford Explorer	1999	Passenger Truck	0.2211	0.0028	0.00070	1.8668	1.8668
Honda Pilot	2004	Passenger Car	0.1564	0.0020	0.00049	1.4788	1.4788
Hyundai Sonata	2011	Passenger Car	0.1564	0.0020	0.00049	1.4788	1.4788
Subaru Forester	2016	Passenger Car	0.1564	0.0020	0.00049	1.4788	1.4788
Toyota Prius	2016	Passenger Car	0.1564	0.0020	0.00049	1.4788	1.4788
Nissan Leaf	2016	Passenger Car	0.1564	0.0020	0.00049	1.4788	1.4788
Ram 2500	2016	Light Commercial Truck	0.2350	0.0030	0.00075	2.0597	2.0597
Ford Explorer	2016	Passenger Truck	0.2211	0.0028	0.00070	1.8668	1.8668

TABLE 3 Summary of Case Study Data Set

Type of Operation	Commute Travel
Trip Purpose	Commute trip from home to workplace
Number of Trips	5 (March 7 – March 11, 2016)
Total Distance (mile)	14.5
Total Duration (minute)	67.7 (60.9 recorded)
Average Speed (mph)	12.8

TABLE 4 Comparative Total Energy Consumption (gallons) and Emissions (grams) of Home-to-Work Trips Based on Eight Vehicles Models

Vehicle Model	Fuel	CO_2	$PM_{2.5}$	CO	NO_x
1999 Ford Explorer	1.16	10,977	0.38	177.91	27.67
2004 Honda Pilot	0.87	8,215	0.12	60.55	3.82
2011 Hyundai Sonata	0.86	8,149	0.07	28.35	0.87
2016 Subaru Forester	0.67	6,360	0.05	15.23	0.61
2016 Toyota Prius	0.67	6,360	0.05	15.23	0.61
2016 Nissan Leaf	0.67	0	0	0	0
2016 Ram 2500	0.83	7,840	0.06	19.63	1.04
2016 Ford Explorer	0.81	7,706	0.06	18.37	0.93

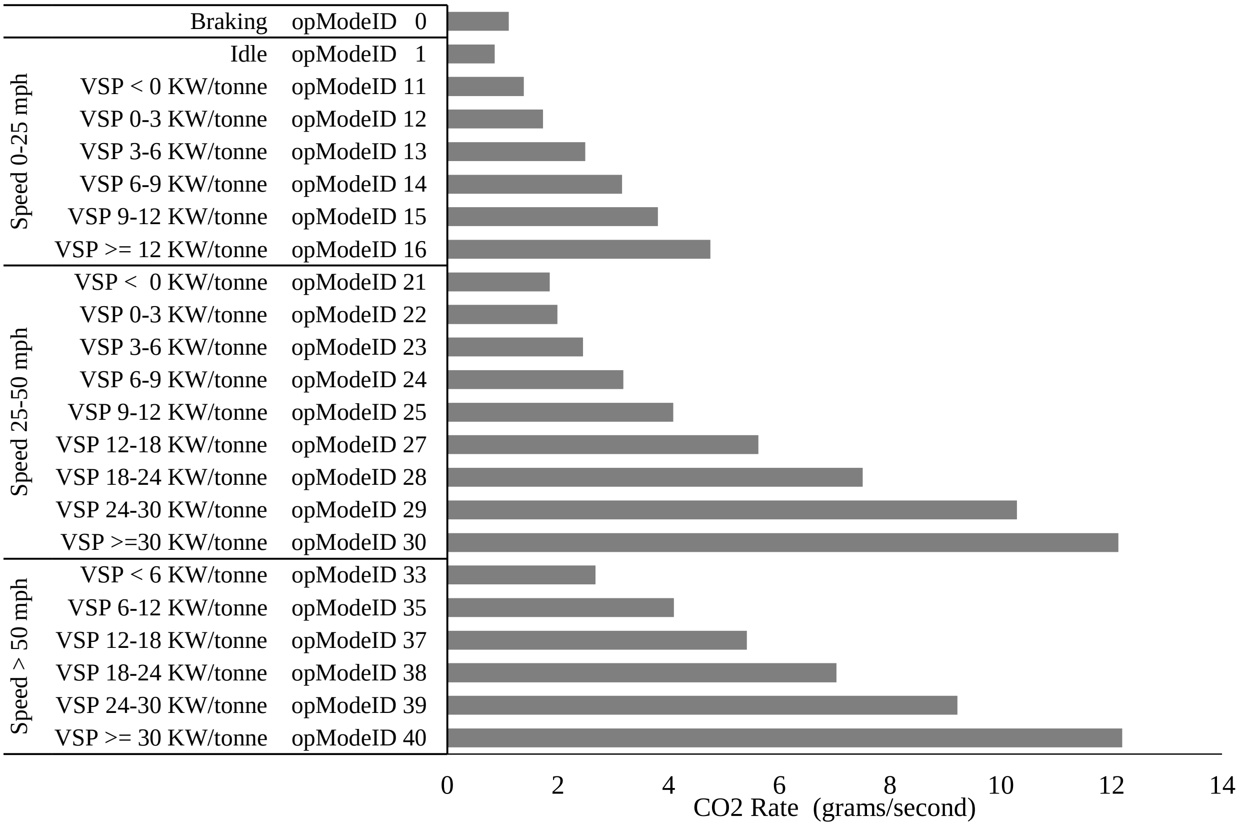

FIGURE 1 Example CO2 Emission Rates by VSP Bin for Passenger Trucks (MY 2016)

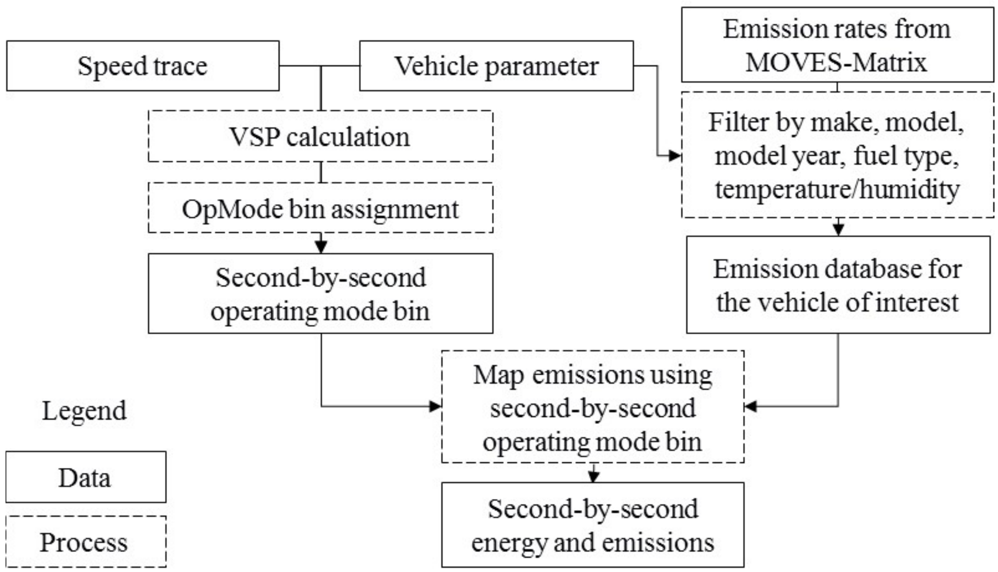

FIGURE 2 MMC Algorithm Design

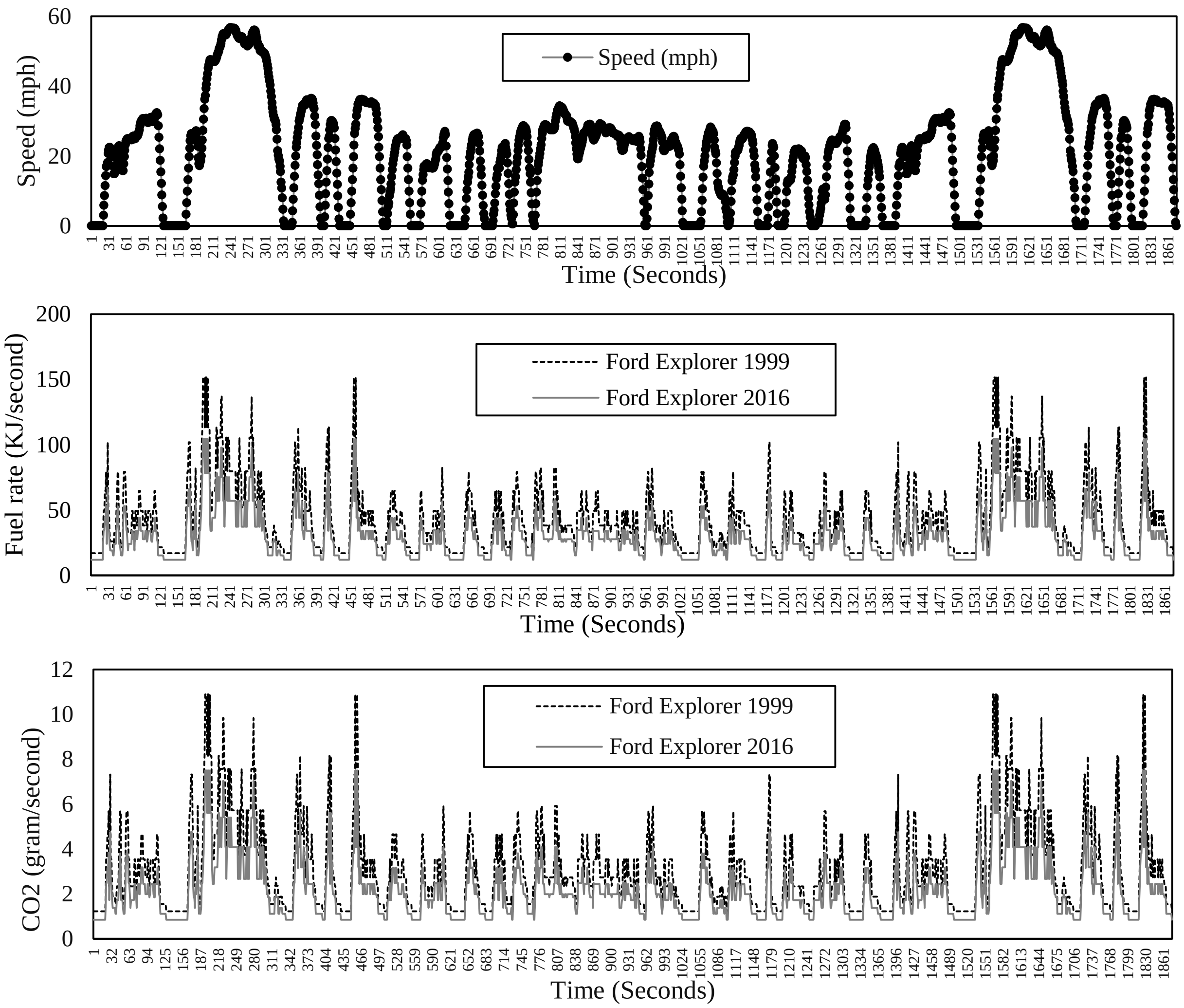

FIGURE 3 a) FTP/EPA75 Second-by-Second Driving Cycle, b) Fuel Consumption Rate, and c) CO_2 Emission Rate*

***Fuel and emission rate of passenger truck (MOVES source type ID = 31, MY = 1999, 2016) are used to represent rate of Ford Explorer**

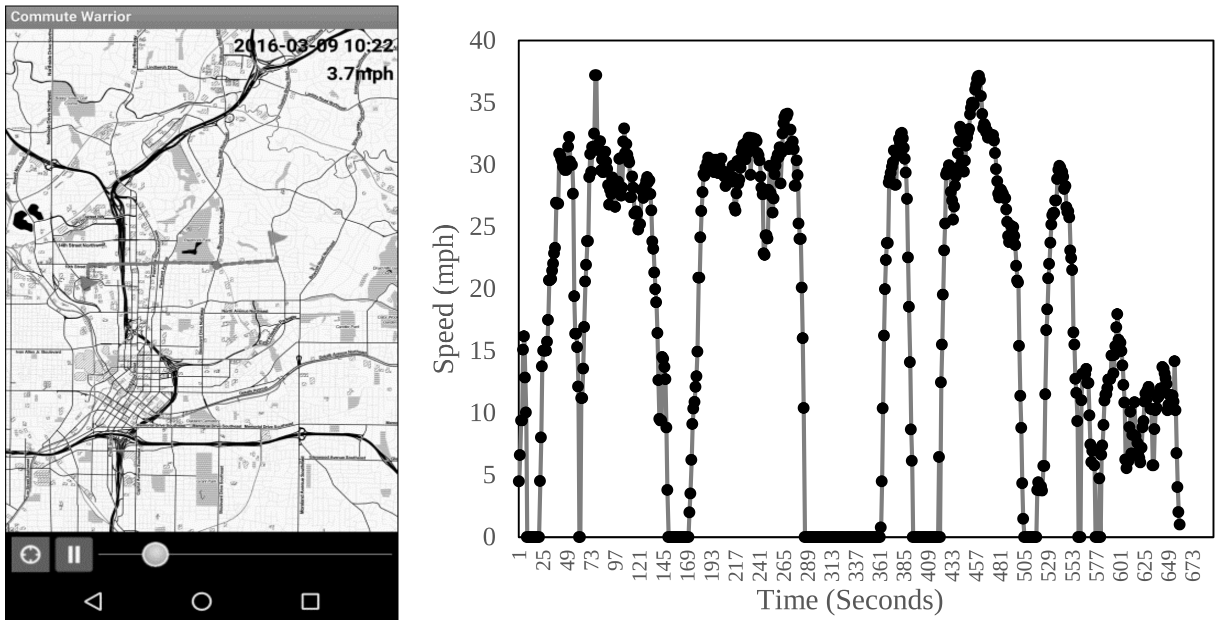

FIGURE 4 Home-to-Work Monitored Trip and Speed Trace

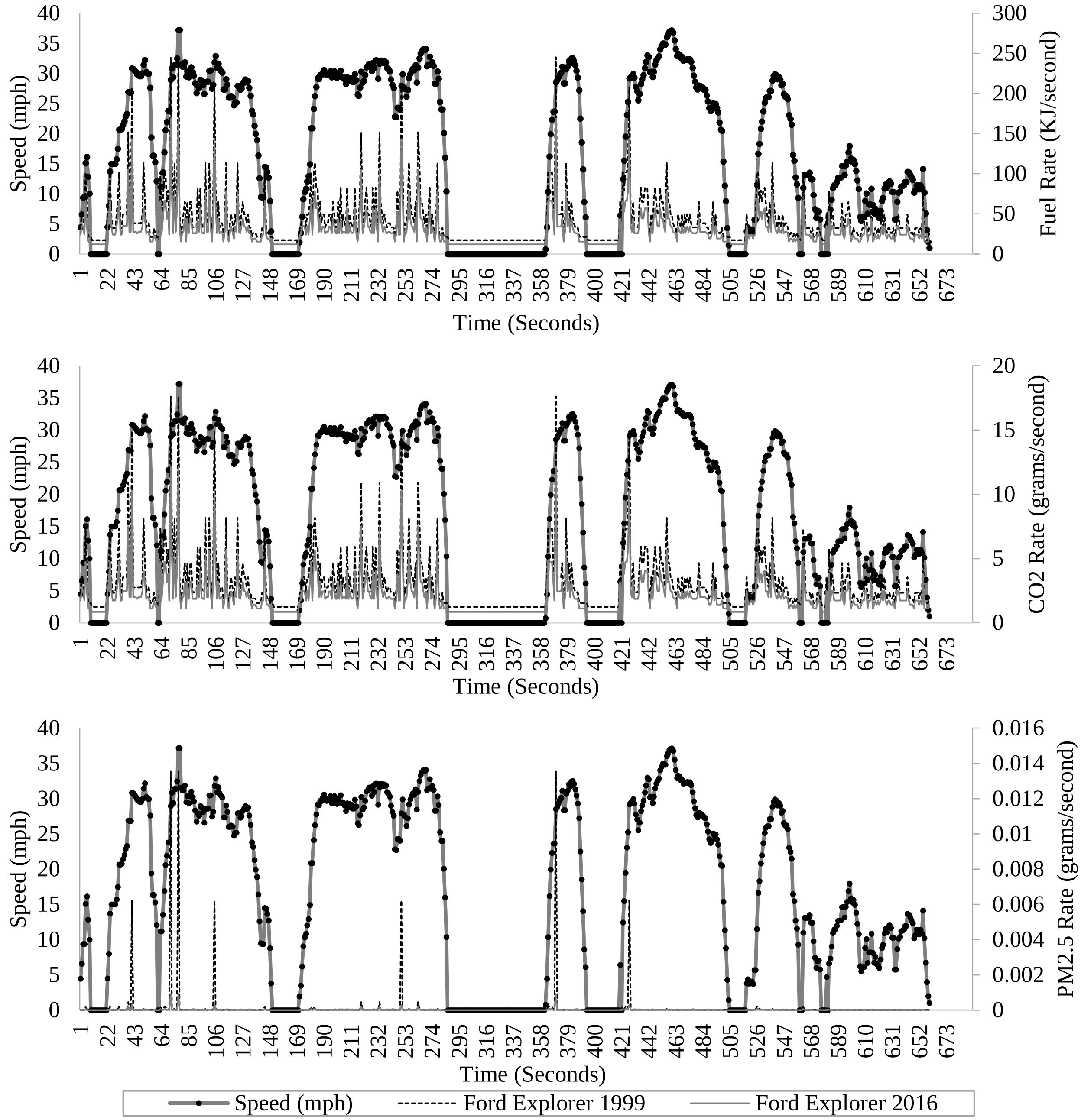

FIGURE 5 Second-by-Second Speed, Fuel Consumption and Emission Rate*

***Passenger truck fuel and emission rates (MOVES source type ID = 31, MY = 1999, 2016) are used to represent rate of Ford Explorer**

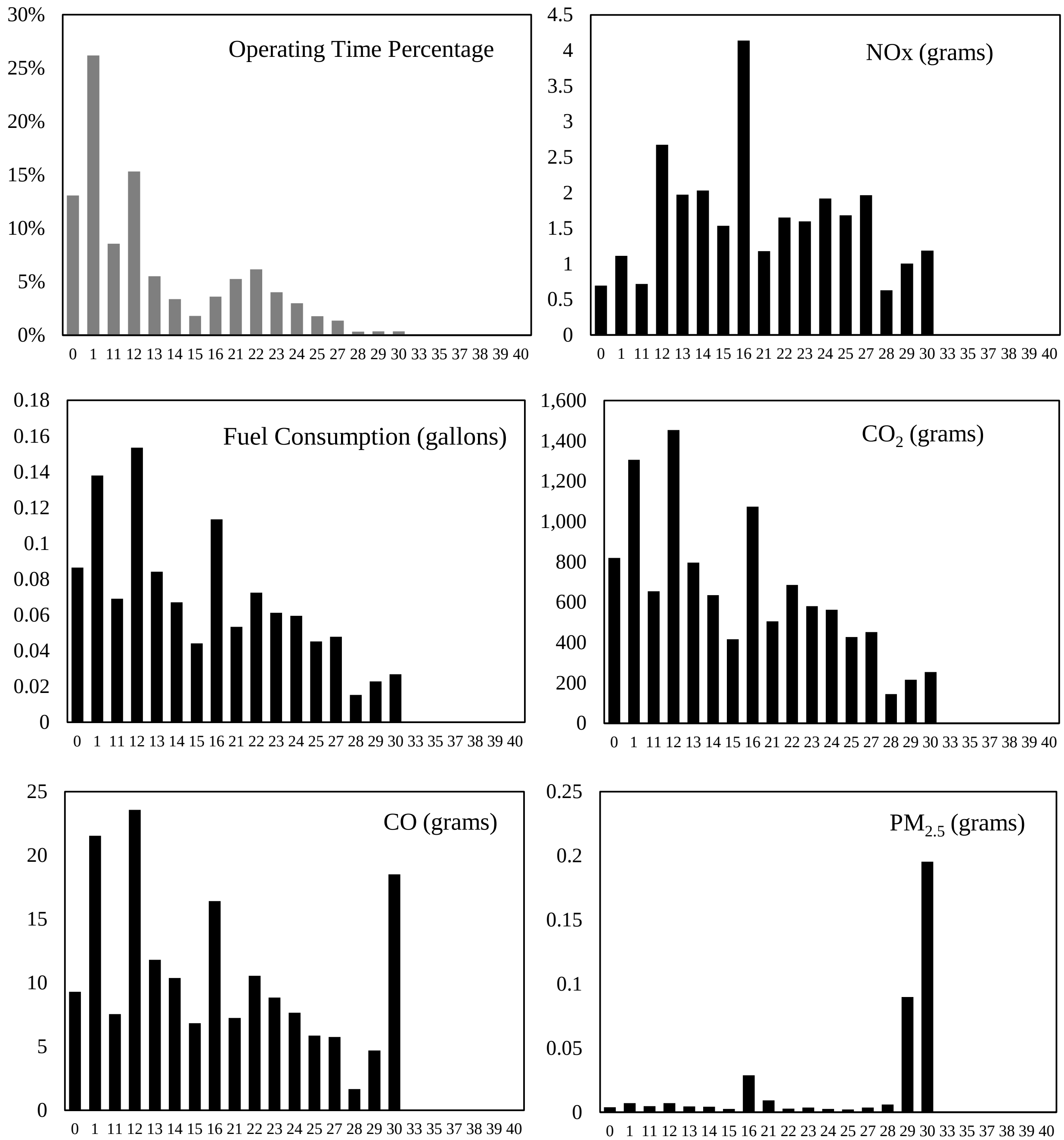

FIGURE 6 Operating Time Percentage and Emissions for Each Operating Mode Bin for the 1999 Ford Explorer*

***Passenger truck fuel and emission rates (MOVES source type ID = 31, MY = 1999, 2016) are used to represent rate of Ford Explorer**