MOVES2010a Model Project-Scale Emission Estimates

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ABSTRACT

A new function introduced in the U.S. Environmental Protection Agency's (EPA) MOVES2010a model is the ability to compute emissions for the project-scale. Different options are available for predicting aggregated link-level emissions, including specifying link average speed using default drive cycles; average second-by-second speed profiles (link drive schedules) representing the vehicle fleet; and user-defined drive cycles by individual vehicle type (operating mode distributions). Examples of how MOVES can be used for advanced applications at the project-scale, where the spatial variation of emissions may be important (i.e., vehicle operation near traffic control devices) and where the spatial and temporal variation of emissions may be important (i.e., linking MOVES emissions and traffic simulation models) are offered. Vehicle activity and emissions are contrasted a number of different ways. Vehicle speed and vehicle-specific power trajectories are presented as a function of distance and time. The effects of changes in the modal operation of vehicles (i.e., cruise speeds and deceleration and acceleration rates) are examined. Emission trajectories are also presented reflecting differences in cruise speeds and deceleration and acceleration rates. A new concept of "op-mode look-up tables" is illustrated for linking MOVES emission results with traffic micro-simulation models.

INTRODUCTION

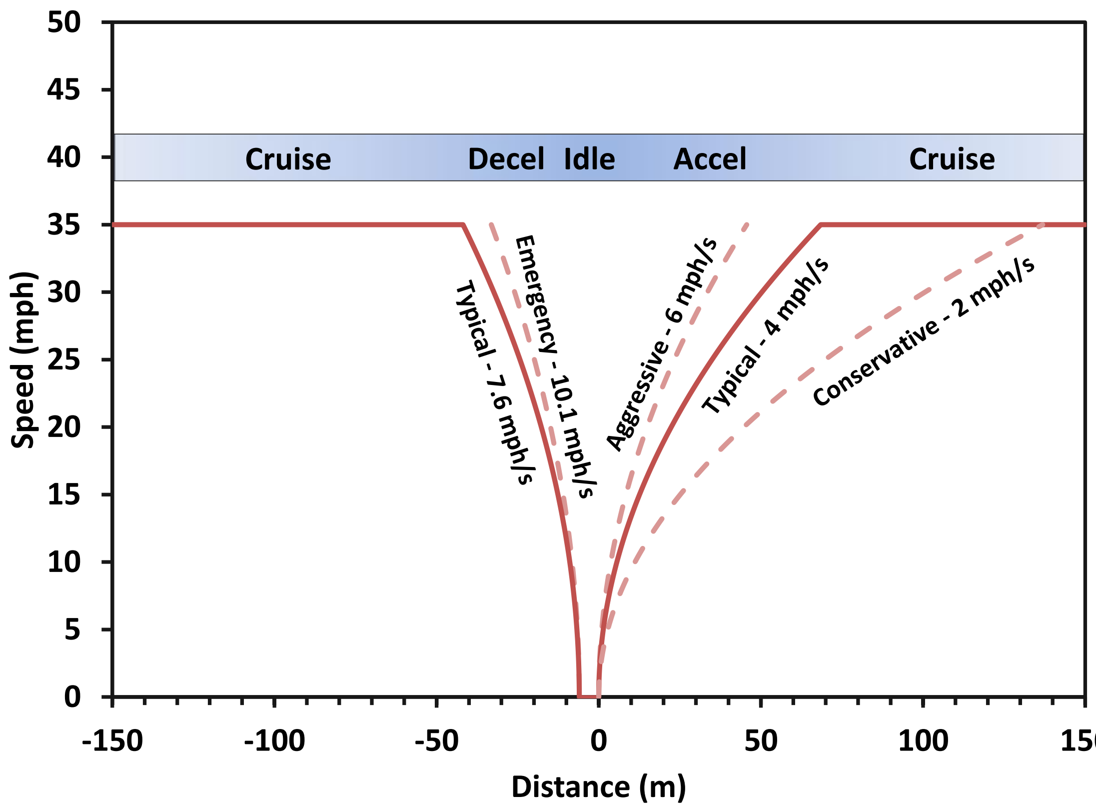
This presentation provides emissions computed with the U.S. Environmental Protection Agency's (EPA) MOVES2010a[1] model (2010830 database) at the project scale. This is an update to a presentation[2] made at the Air & Waste Management Association's Annual Conference & Exhibition in 2010. Emphasized are modal emissions of selected pollutants on a highway link and the variation of vehicle emissions for the different operating modes (OpModes) established in the MOVES model. Vehicle operating conditions representative of highway travel for cruise, deceleration, idle, and acceleration are characterized for various speeds, deceleration/acceleration rates, and roadway grades. Results for the different emission processes relevant to on-road vehicle operation are presented as appropriate, including running exhaust, crankcase running exhaust, brake wear, and tire wear. Vehicle emissions are provided for the different OpMode bins – categories of vehicle speed and vehicle specific power (VSP) representing braking, idling, low and medium speed coasting, cruising/accelerating, running, and tire wear.

MOTOR VEHICLE ACTIVITY ON HIGHWAYS

Emission rates of mobile sources vary by operating mode on highways, especially at interchanges and intersections. The basic operating components of a vehicle traveling on a highway are cruise, decelerate, idle, and accelerate. Vehicles operate in more or less a cruise mode on uncongested highways, such as freeways and arterials at midblock. Invariably, there are fluctuations in travel speeds as drivers weave through traffic with relatively subtle changes in vehicle acceleration and deceleration rates. More dramatic changes in vehicle operation occur near traffic controls, such as signals at intersections, ramp meters, and roundabouts; for special circumstances, such as accidents and lane closures; or on highly congested facilities.

To illustrate, consider a simple speed trajectory of a single car operating on an urban arterial controlled with traffic signals. As depicted in Figure 1, travel can be described by a steady cruise speed at midblock; decelerating to a full stop for a red light; idling until the light turns green; and after a brief start-up delay, accelerating back to a steady cruise speed. If a vehicle approaches an intersection during the green signal phase of a traffic light, travel can be characterized by a fairly steady cruise speed through the intersection. There are other considerations with numerous vehicles stopping and starting at an intersection over many signal cycles during an hour. For instance, heavy trucks decelerate and accelerate at slower rates than passenger cars. Drivers tend not to decelerate at a constant rate, but by a combination of coasting and light and heavy

Figure 1. Vehicle Travel Speeds Approaching and Departing a Traffic Control.



braking. Acceleration rates are initially higher when moving from a complete stop away from an intersection, becoming progressively lower to make a smooth transition to cruise speed. In the case of an uncongested intersection, the rates of vehicles approaching and departing the intersection are in equilibrium. Some vehicles may slow, and then speed up to join the dissipating queue without having to come to a full stop. Once the queue clears, approaching vehicles during the remainder of the green phase will cruise through the intersection virtually unimpeded. In the case of a congested intersection, the rate of vehicles approaching the intersection is greater than the rate of departure so that no vehicle can travel through without stopping. Vehicles approaching a traffic signal, whether it is red or green, will have to come to a full stop and idle for one or more cycles before departing the intersection.

MOVES uses vehicle speed in combination with VSP (the power to weight ratio of the vehicle) to characterize vehicle activity as different OpModes bins as shown in Table 1. As implemented in the MOVES model, VSP is a function of the rolling resistance of the vehicle (terms A and B), aerodynamic drag (term C), average vehicle velocity (v, m/s), vehicle acceleration (a, m/s^2), vehicle mass and fixed mass factor (m and m_{fixed}, metric tons), gravitation constant (g, m/s^2), and roadway grade (θ):

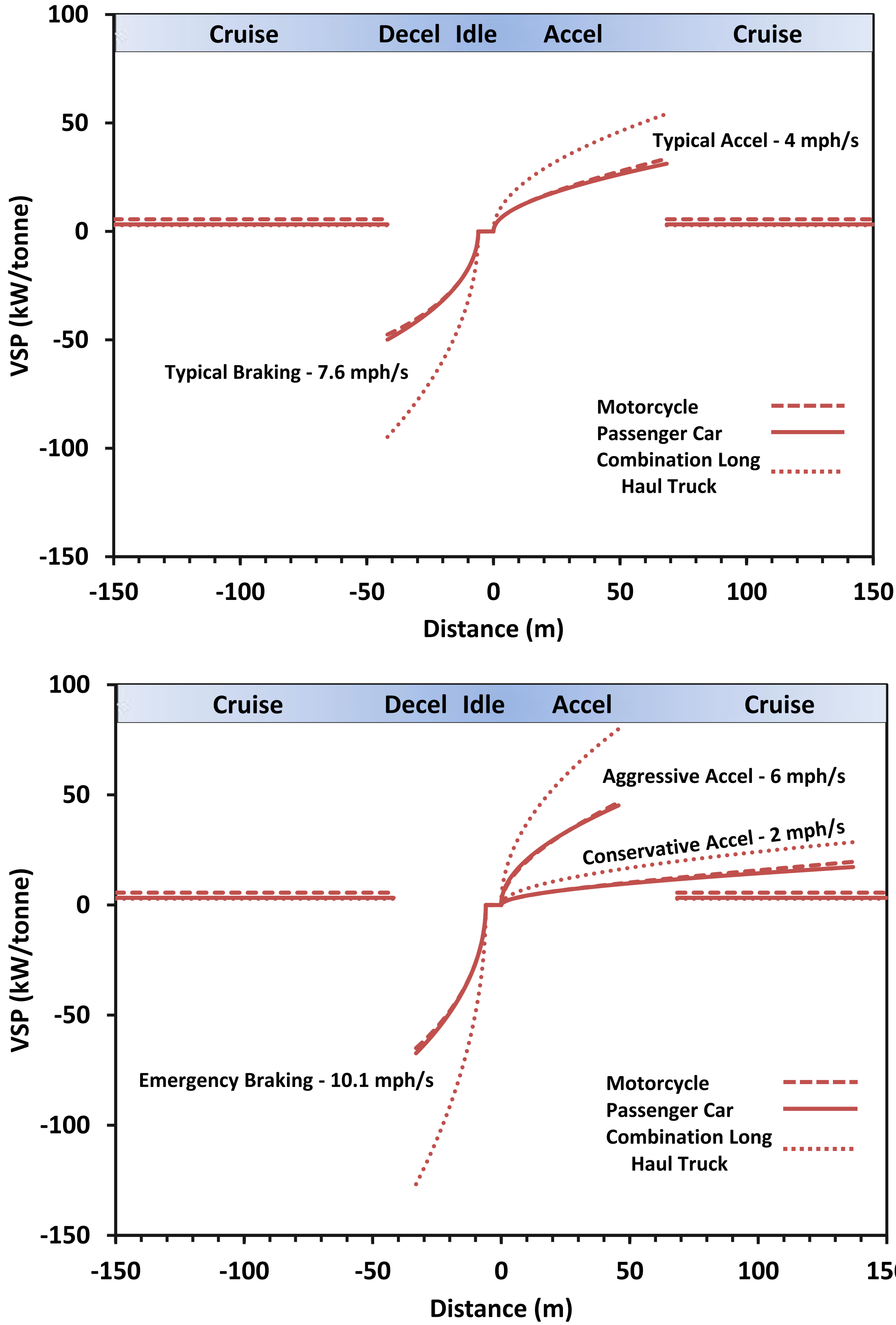
$$VSP = \frac{A\,v + B\,v^2 + C\,v^2 + m\,a\,v + m\,v\,g\,\sin\theta}{m_{fixed}} \qquad (\mathbf{Eq.\,1})$$

The single car trajectory viewed in terms of VSP is shown in Figure 2. The top panel provides VSP profiles based on typical deceleration and acceleration rates for different

Table 1. OpMode Bins Definitions (OpMode IDs).

<table>
<tr><th rowspan="2">Description</th><th rowspan="2">VSP (kW/tonne)</th><th colspan="3">Speed (mph)</th></tr>
<tr><th>1 – 25</th><th>25 – 50</th><th>≥ 50</th></tr>
<tr><td rowspan="11">Cruise / Acceleration</td><td>> 30</td><td rowspan="7">16</td><td>30</td><td>40</td></tr>
<tr><td>27 – 30</td><td rowspan="2">29</td><td rowspan="2">39</td></tr>
<tr><td>24 – 27</td></tr>
<tr><td>21 – 24</td><td rowspan="2">28</td><td rowspan="2">38</td></tr>
<tr><td>18 – 21</td></tr>
<tr><td>15 – 18</td><td rowspan="2">27</td><td rowspan="2">37</td></tr>
<tr><td>12 – 15</td></tr>
<tr><td>9 – 12</td><td>15</td><td>25</td><td rowspan="2">35</td></tr>
<tr><td>6 – 9</td><td>14</td><td>24</td></tr>
<tr><td>3 – 6</td><td>13</td><td>23</td><td rowspan="2">33</td></tr>
<tr><td>0 – 3</td><td>12</td><td>22</td></tr>
<tr><td>Coasting</td><td>< 0</td><td>11</td><td>21</td><td>–</td></tr>
<tr><td>Braking</td><td>–</td><td colspan="3">0</td></tr>
<tr><td>Idling</td><td>–</td><td colspan="3">1</td></tr>
<tr><td>Running</td><td>–</td><td colspan="3">301 – 316</td></tr>
<tr><td>Tire Wear</td><td>–</td><td colspan="3">400 – 416</td></tr>
</table>

Figure 2. Example Vehicle VSP Trajectories Through a Traffic Control.



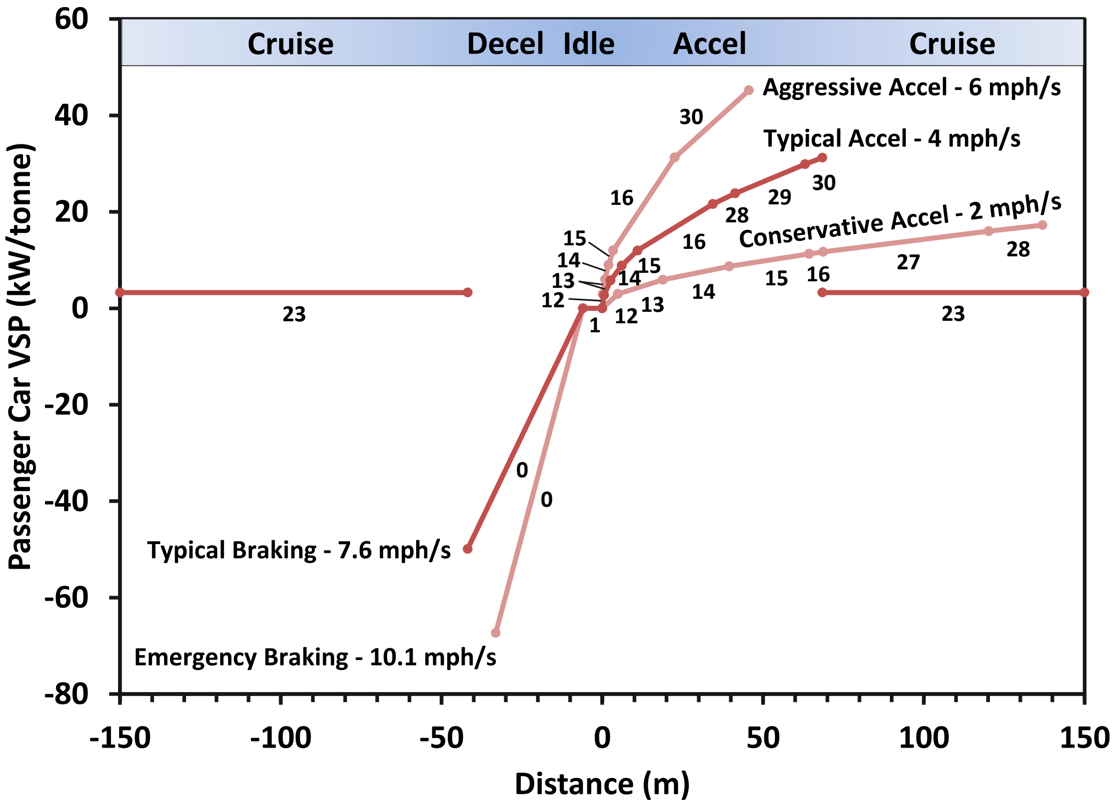
vehicle types. The bottom panel provides VSP profiles for emergency braking and conservative and aggressive acceleration rates for different vehicle types. The single car trajectory viewed in terms of OpMode bin is shown in Figure 3, overlaying the segments that represent the speed and VSP ranges of each specific bin.

METHODOLOGY

EPA's MOVES model provides a tool for predicting the emission rates associated with changing driving patterns on highways via three options: 1) estimates of vehicle speeds based on travel time and distance; 2) link drive schedules defining second-by-second changes in speed and highway grade; and 3) operating mode distributions, i.e., the time fraction time starting, braking, idling, coasting, cruising and accelerating, and so on.

Emissions were calculated for carbon monoxide (CO) during the morning peak-hour (7 to 8 am); daily average volatile organic compounds (VOC) and nitrogen oxides (NOx), which are the precursors to ozone formation; plus annual average particulate matter (PM) of size less than or equal to 2.5 micrometers, carbon dioxide equivalent greenhouse gases (CO2e), and benzene. The analysis was conducted accounting for the applicable emission components specific to vehicle operation on major highway facilities, e.g., running exhaust, crankcase running exhaust, brake wear, and tire wear. Results are provided for calendar year 2010.

Figure 3. Example Vehicle OpMode Trajectories Through a Traffic Control.



Typically, highest CO levels are observed in the wintertime and highest ozone levels are observed in the summertime. Accordingly, CO emissions were based on temperature and humidity measurements made during January, which is the coldest month of the year. VOC and NOx emissions were based on temperature and humidity measurements made during July, which is the warmest month of the year. Annual variations in temperature and humidity were considered when computing annual average emissions.

National scale information provided in the MOVESDB20100830 database were used at the project scale for age distribution, fuel supply, fuel formulation, meteorology data, and inspection/maintenance programs.

Highway Link Emissions

The link drive schedule option was employed to differentiate emissions on a highway link by the fundamental components of vehicle cruising, decelerating, idling, and accelerating. The MOVES model differentiates engine idling on and off the roadway network. MOVES computes idle emission rates on a highway link by specifying a link average speed of 0 mph or a link drive schedule consisting of a second-by-second sequence of 0 mph speeds or an operating mode distribution time fraction of 1 for OpModeID 1. MOVES can also represent emissions produced during long periods of engine idling activity associated with long-haul diesel trucks, such as overnight idling at truck stops. Link-level idle emission rates are provided in this analysis and not off-network extended idle emission rates.

MOVES internally converts link drive schedule information into operating mode distributions distinguished by VSP and instantaneous speed. Separate links were defined to segregate cruise, deceleration, idle, and acceleration modal emission components. Link drive schedules were created for different speeds, deceleration/ acceleration rates, and roadway grades. Deceleration rates of 7.6 mph/s and 10.1 mph/s were selected to denote typical and emergency situations, respectively. Acceleration rates of 2 mph/s, 4 mph/s, and 6 mph/s were selected to indicate conservative, average, and aggressive rates, respectively. Highway grades of 0%, ±2%, ±4%, and ±6% were selected – for perspective, 6% is a rather steep highway grade.

Vehicle Emissions

The operating mode distribution option was employed to differentiate emissions from vehicles driving in each of the OpMode categories of braking, idling, low and medium speed coasting, cruise/acceleration, running, and tire wear. Separate links were defined to represent a specific OpMode bin. For example, for OpMode 0 (braking), a corresponding link ID of 0 was specified with an OpMode fraction set to 1 for each source type (vehicle type), and pollutant/process. Emission results were segregated for each individual vehicle type.

RESULTS AND DISCUSSION

Figure 4 displays modal emissions in grams normalized to source hours operating (SHO) activity for CO, PM2.5, NOx, VOC, CO2e, and benzene as computed with the MOVES model for a range of positive (uphill), negative (downhill), plus zero (level) highway grades. Source hours operating is the fundamental activity basis for the running, tire wear, and brake wear processes in MOVES. It represents the total hours of all sources within a source type spent operating on the roadway network for the given time and location specified[3] computed by:

$$SHO = \frac{Link\ Volume \times Link\ Length}{Link\ Average\ Speed} \qquad (\mathbf{Eq.\ 2})$$

For idle emissions, SHO is the link volume multiplied by the time specified.

The modes of vehicle operation depicted include steady-state cruise at 35 mph, decelerate from 35 mph at a typical rate of 7.6 mph/s, idle, and accelerate to 35 mph at a typical rate of 4 mph/s. The acceleration mode produces the highest emission rate on grams per source hours operating basis. However, nearby ambient concentrations are influenced by the magnitude of emissions expressed as mass per unit time per unit distance traveled. When the effects of travel time are taken into account, modal emissions for idling vehicles can be predominant, especially at highly congested traffic controls. Idle times can be as high as a minute or more for over-capacity conditions, while decelerating from 35 mph to a full stop may take less than 5 s over a distance of 36 m and accelerating from a full stop to 35 mph may take less than 9 s over a distance of 68 m.

Figure 5 presents modal emissions computed with the MOVES model in grams per source hours operating for PM2.5 as a function of OpMode bin and vehicle type (source type ID). The top panel shows the OpMode bins for vehicle exhaust and the bottom panel shows the OpMode bins for brake and tire wear. Disproportionate emissions of PM2.5 for all vehicle types are associated with OpModes 29 and 30, which are the highest VSP classes (i.e., greater than 24 kW/tonne) in the moderate speed range (i.e., 25 to 50 mph).

IMPLICATIONS FOR EVALUATING HIGHWAY PROJECTS

Figure 6 provides an illustration of how modal emissions may be apportioned spatially near a signalized intersection for use in dispersion modeling. Modal emissions may be assigned to overlapping highway segments, which can be readily determined. The length of a vehicle queue is dependent on the number of vehicles subject to stopping at a red signal. Vehicles approaching a red traffic signal decelerate over a distance extending from the intersection stop line back to the stopping distance required for the last vehicle in the queue. The average stopping distance can be calculated from the average deceleration rate and the average cruise speed. Similarly, vehicles departing a queue when the light turns green accelerate over a distance extending from the end of the vehicle queue to the distance required for the first vehicle to reach the cruise speed.

Figure 4. Modal Emissions (g/SHO) for Calendar Year 2010.

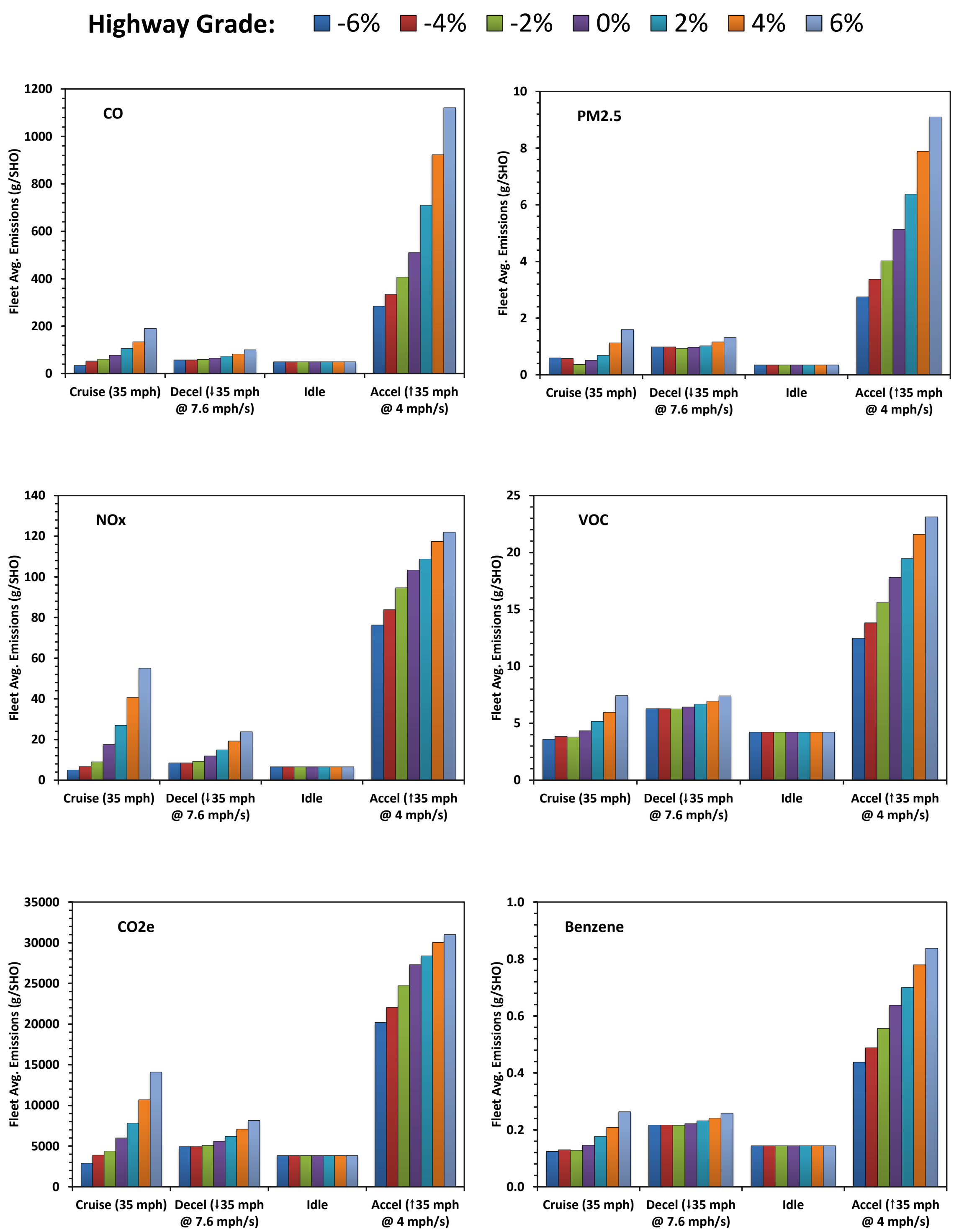


Figure 5. Modal PM2.5 Emissions (g/SHO) by OpMode for Calendar Year 2010.

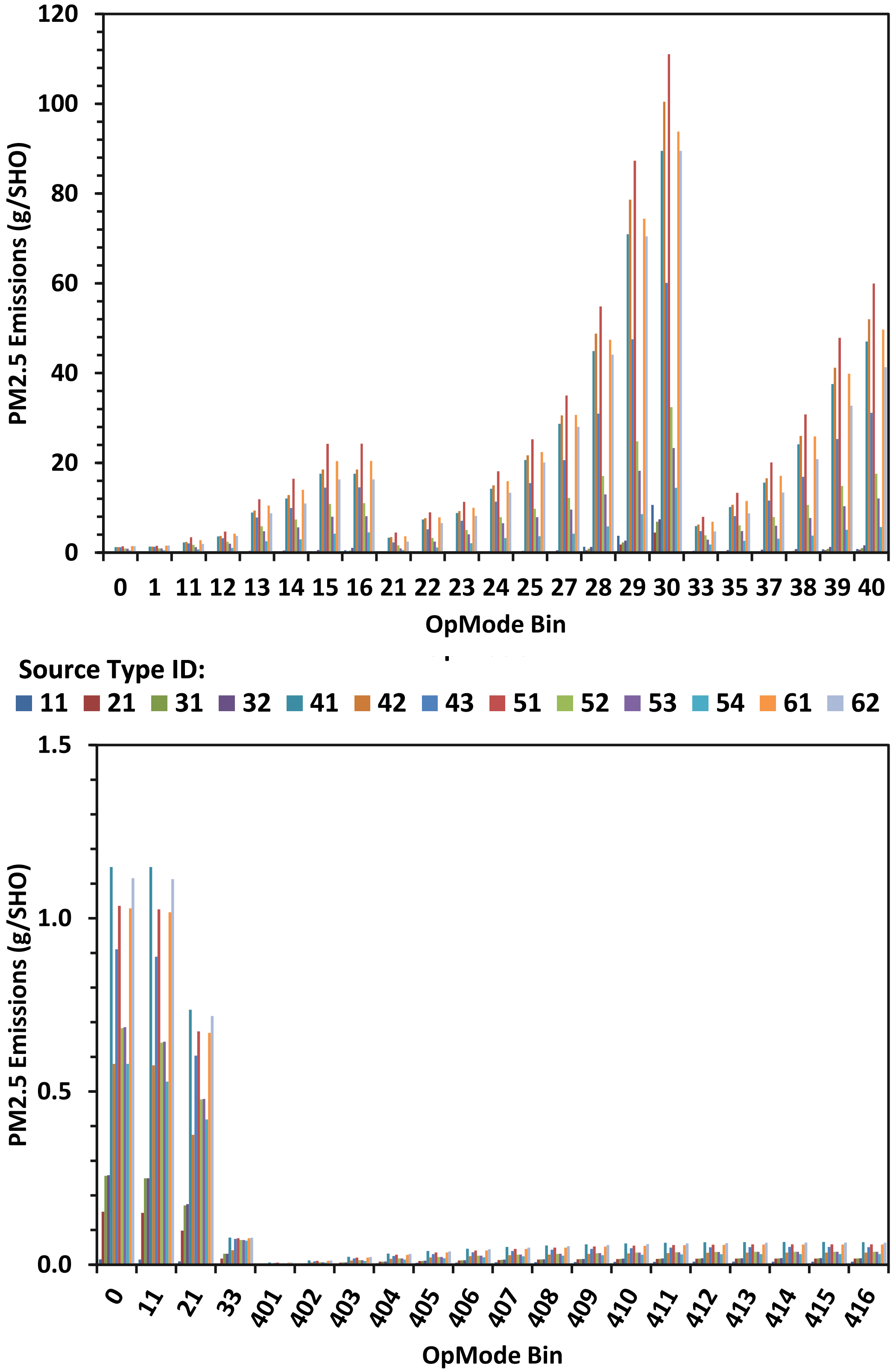
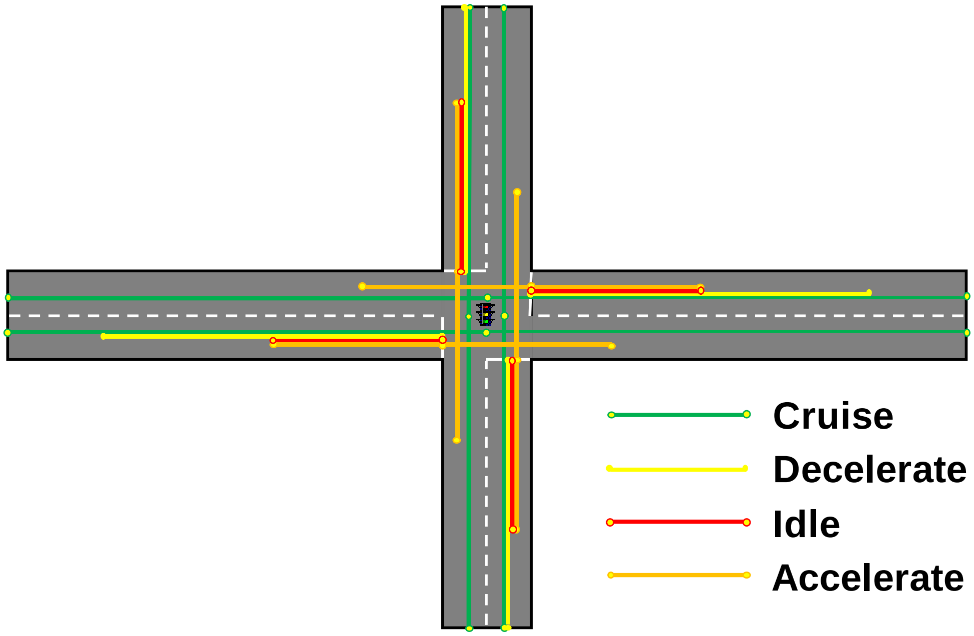


Figure 6. Spatial Allocation of Modal Emissions.

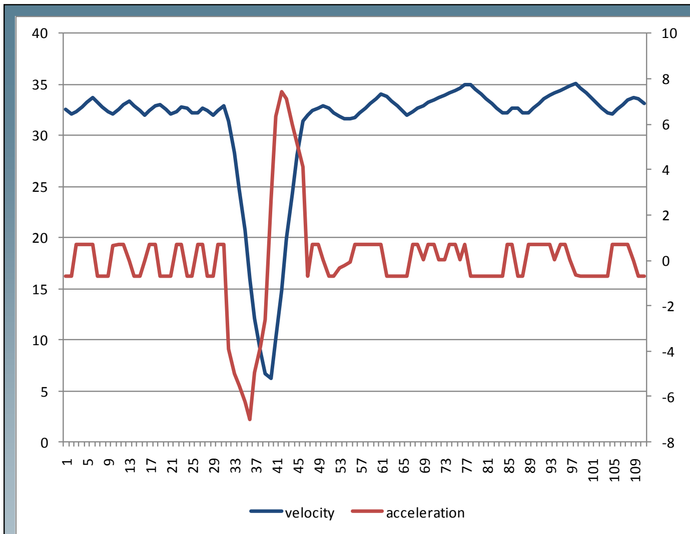


Traffic micro-simulation models can be used to characterize the link drive schedules or operating mode distributions required by MOVES, i.e., traffic model output used as MOVES model input. The linkages between the models are a current topic of research. An option proposed here is to link the vehicle activity output from traffic micro-simulation models with the emissions output from MOVES – special output in the form of OpMode look-up tables to characterize emission results for each operating mode bin as illustrated in Figure 5. One advantage of an OpMode look-up table is that MOVES can be run independently of precisely defined link drive schedules or operating mode distributions. The vehicle activity provided by traffic micro-simulation models is the information needed to determine the operating mode of a vehicle based on speed and VSP (see Figure 7[4]). This activity can be matched to the OpMode bin to establish emissions.

There are other advantages to employing OpMode look-up tables. MOVES aggregates emissions spatially and temporally over a link simulation while traffic micro-simulation models track vehicle activity in space and time. Accounting for the spatial and temporal variation of vehicle emissions can be important in air quality and public exposure assessments. MOVES OpMode look-up tables could be used in traffic micro-simulation models to similarly track vehicle emissions in space and time.

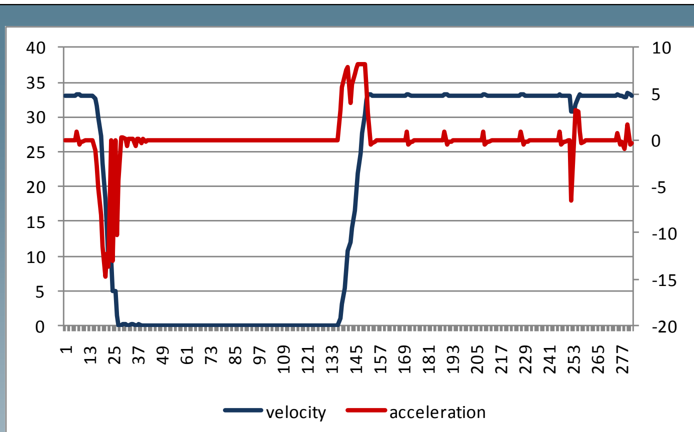
There are also some savings in computational times that may be realized for large applications consisting of thousands of highway links. Instead of importing traffic simulation information into MOVES for analysis, the results can be linked to MOVES OpMode look-up tables of emissions achieving much faster processing times. The feasibility of employing OpMode look-up tables as suggested here is being investigated by researchers at the University of California Irvine in a study funded by the University of California Transportation Center[5]. They are considering the task of estimating

Figure 7. Example Vehicle Trajectories from Traffic Micro-Simulation Models[4].



VISSIM
Vehicle Record File
(.fzp)

t	VehNr	DistX	a	v
3600	846	496	-0.58	29.87
3600	841	3020	0.51	31.73
3600	833	3654	-0.72	31.6
3600	829	3734	0.77	32.6
3600	824	3822	0.3	32.48
3600	819	3987	0.77	30.91
3600	832	4500	-0.76	31.68
3600	831	4792	0.53	29.57
3600	827	5354	-0.04	30.46
3600	826	5429	0.7	30.94
3600	825	5517	-0.63	31.41
3600	822	6127	0.89	31.5
3600	818	6195	0.81	31.78
3600	814	6274	0.41	32.21
3600	813	6527	-0.48	32.71
3600	848	359	0.65	28.94



Paramics
vehicle-trajectory.csv

time	ID	x	y	v	a
3600.5	848	-68.27	1634.37	0.52	0.32
3600.5	856	-1286.25	1634.37	34.38	0
3600.5	861	-2306.02	1634.37	33.09	0
3600.5	862	-2435.31	1634.37	33.46	0
3600.5	863	-2615.37	1634.37	33.64	0
3600.5	842	19.68	1646.47	0	0
3600.5	843	40.97	1646.47	0.21	0.18
3600.5	844	71.3	1646.47	2.66	-0.84
3600.5	847	111.63	1646.47	3.64	-0.63
3600.5	849	150.51	1646.47	3.35	-0.59
3600.5	850	195.95	1646.47	10.75	-3.85
3600.5	851	352.91	1646.47	22.15	-5.17
3600.5	853	681.48	1646.47	32.73	-2.15
3600.5	855	1297.49	1646.47	32.91	0
3600.5	858	1843.25	1646.47	31.63	0
3600.5	860	2144.19	1646.47	32.91	0

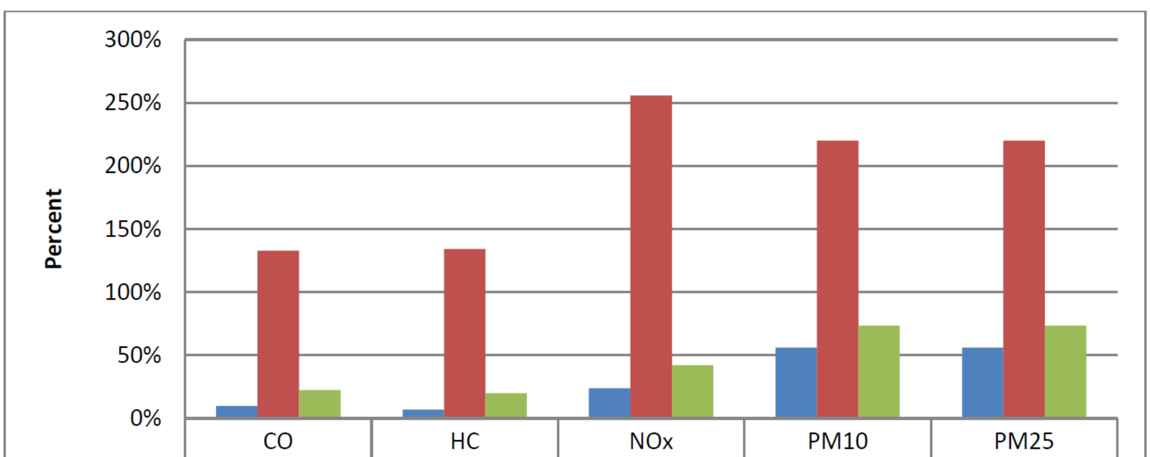
emissions for 5000 vehicles for each highway link on a large transportation network (some 2000 links or 10 million vehicle trajectories). They successfully demonstrated that emission results using the OpMode look-up table methodology matched the results obtained from MOVES with direct OpMode distribution input for a second-by-second trajectory of one vehicle. Computation times in applying individual trajectories of about 5000 vehicles generated from traffic micro-simulation to an OpMode lookup table of emissions are on the order of 5 minutes. Initial results from the research indicate large differences in emissions if characterizing vehicle activity employing second-by-second vehicle trajectories versus link average speed, especially for congested arterial roadways (see Figure 8[5]).

SUMMARY

A dynamic range of vehicle operation occurs near traffic controls in terms of vehicle activity (speed, vehicle specific power, operating mode) and emissions. The most basic forms of vehicle operating modes are steady-state cruising, decelerating, idling, and accelerating. Emissions on a grams per source hours operating basis are highest during acceleration and lowest during cruise, deceleration, and idle. However, when the effect of moving vehicles is taken into account, idle emissions on a highway link can be highest. MOVES characterizes vehicle activity by speed and VSP classes as OpMode bins. PM 2.5 emissions are at a maximum in the highest VSP ranges (< 24 kW/tonne) and the moderate speed range (25 to 50 mph).

The spatial and temporal variation of vehicle emissions at traffic controls may require special analysis to properly allocate link-level emissions.

Figure 8. Percent Differences in Emission Results Obtained Using Vehicle Trajectories Versus Average Link Speeds[5].



	CO	HC	NOx	PM10	PM25
FREEWAY	10%	7%	24%	56%	56%
ARTERIAL	133%	134%	256%	220%	220%
TOTAL	22%	20%	42%	73%	73%

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KEYWORDS

Mobile sources, highway emissions, emission factors, emissions modeling, MOVES model.