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TECHNICAL PAPER

Using a traffic simulation model (VISSIM) with an emissions model (MOVES) to predict emissions from vehicles on a limited-access highway

Hatem Abou-Senna,* Essam Radwan, Kurt Westerlund, and C. David Cooper
Department of Civil, Environmental, and Construction Engineering, University of Central Florida, Orlando, Florida, USA
**Please address correspondence to: Hatem Abou-Senna, Department of Civil, Environmental and Construction Engineering (CECE), University of Central Florida (UCF), 4000 Central Florida Blvd., Eng. Building II, Orlando, FL 32816-2450, USA; e-mail: Hatem.Abou-senna@ucf.edu*

The Intergovernmental Panel on Climate Change (IPCC) estimates that baseline global GHG emissions may increase 25–90% from 2000 to 2030, with carbon dioxide (CO_2) emissions growing 40–110% over the same period. On-road vehicles are a major source of CO_2 emissions in all the developed countries, and in many of the developing countries in the world. Similarly, several criteria air pollutants are associated with transportation, for example, carbon monoxide (CO), nitrogen oxides (NOx), and particulate matter (PM). Therefore, the need to accurately quantify transportation-related emissions from vehicles is essential. The new U.S. Environmental Protection Agency (EPA) mobile source emissions model, MOVES2010a (MOVES), can estimate vehicle emissions on a second-by-second basis, creating the opportunity to combine a microscopic traffic simulation model (such as VISSIM) with MOVES to obtain accurate results. This paper presents an examination of four different approaches to capture the environmental impacts of vehicular operations on a 10-mile stretch of Interstate 4 (I-4), an urban limited-access highway in Orlando, FL. First (at the most basic level), emissions were estimated for the entire 10-mile section "by hand" using one average traffic volume and average speed. Then three advanced levels of detail were studied using VISSIM/MOVES to analyze smaller links: average speeds and volumes (AVG), second-by-second link drive schedules (LDS), and second-by-second operating mode distributions (OPMODE). This paper analyzes how the various approaches affect predicted emissions of CO, NOx, PM2.5, PM10, and CO_2. The results demonstrate that obtaining precise and comprehensive operating mode distributions on a second-by-second basis provides more accurate emission estimates. Specifically, emission rates are highly sensitive to stop-and-go traffic and the associated driving cycles of acceleration, deceleration, and idling. Using the AVG or LDS approach may overestimate or underestimate emissions, respectively, compared to an operating mode distribution approach.

Implications: Transportation agencies and researchers in the past have estimated emissions using one average speed and volume on a long stretch of roadway. With MOVES, there is an opportunity for higher precision and accuracy. Integrating a microscopic traffic simulation model (such as VISSIM) with MOVES allows one to obtain precise and accurate emissions estimates. The proposed emission rate estimation process also can be extended to gridded emissions for ozone modeling, or to localized air quality dispersion modeling, where temporal and spatial resolution of emissions is essential to predict the concentration of pollutants near roadways.

Introduction

Emissions of greenhouse gases (GHGs), primarily carbon dioxide (CO_2), are contributing to global climate change, which is believed by many to be one of the most critical environmental issues facing the world this century. CO_2 from transportation is expected to remain the major source of total U.S. greenhouse gas emissions (IPCC 2008). To help Florida reduce GHGs, the state adopted the California motor vehicle emission standards for GHGs. Transportation as a whole represents about 40% of Florida's total GHG emissions, second only to the electric utility sector. Also, ambient air quality standards have been established for several pollutants associated with transportation, including carbon monoxide (CO) and particulate matter (PM10 and PM2.5). In addition to these criteria pollutant emissions, motor vehicles emit volatile organic compounds (VOCs) and nitrogen oxides (NOx), both of which are ozone precursors. Nationally, on-road transportation sources are responsible for 21% of VOCs emissions, 32% of NOx emissions, and 50% of CO emissions (NEI, 2008).

Transportation agencies and researchers have a long history of implementing techniques to calculate transportation-related emissions. Traditional methods for creating emission inventories utilized annual average estimates. One comparison of annual estimates with monthly estimates of vehicular emission provided similar results, implying that detailed calculations were not necessary for annual emissions inventories (Cooper and Arbrandt, 2004). Travel demand models have been utilized to

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provide an intermediate level of detail (daily values). However, static planning models were found to ignore individual vehicle behavior, which leads to underestimation of pollutant emissions, as they do not account for link capacity and other dynamic variables. As a result, estimates of emissions based on static planning models suffer from significant biases in different traffic conditions (You et al., 2010). Currently, more accuracy has been established using microscopic analyses through the reduction of time and distance scales while splitting the network links into sublinks and utilizing second-by-second operations to calculate emissions.

The emission factors (EFs) for highway vehicles used in the U.S. GHG Inventory are based on laboratory testing of vehicles. Although the controlled testing environment simulates actual driving conditions, the results from such testing can only approximate real-world conditions and emissions. For some vehicle and control technology types, the testing did not yield statistically significant results within the 95% confidence interval, requiring reliance on expert judgment when developing the EFs (U.S. Environmental Protection Agency [EPA], 2006). In those cases, the EFs were developed based on comparisons of fuel consumption between similar vehicle and control technology categories. Since 95% of transportation GHG emissions are in the form of CO_2 (U.S. EPA, 2009), uncertainty in the CO_2 estimates has a much greater effect on the transportation sector estimates of GHG emissions than uncertainty associated with nitrous oxide (N_2O), methane (CH_4), or hydrofluorocarbons (HFC) emissions. Other vehicular pollutants are important as well. CO is a criterion pollutant with two national ambient air quality standards (NAAQS), and is used in project level analysis. NOx is a criterion pollutant that is very important due to its role (along with volatile organic compounds [VOCs]) in ozone formation. The majority of project-level analyses are conducted to meet a regulatory requirement such as the 1-hr near-road NO_2 standard and PM/CO hotspot conformity requirements. Therefore, the need to accurately quantify transportation-related emissions from vehicles is crucial.

Several analyses have been conducted in the literature to calculate vehicular emissions utilizing different models and techniques, along with numerous factors that contribute to the increase in vehicular emissions, such as traffic volume, speed limit, truck percentage, roadway grade, and temperature. This paper provides a detailed examination of some of those techniques and contributing factors. A limited-access urban highway in Orlando, FL, was modeled using a popular microscopic traffic simulation model, VISSIM, coupled with a U.S. EPA mobile source emissions model, MOVES2010a. Detailed traffic operations generated from VISSIM on a second-by-second basis were input into the MOVES model to quantify emission rates.

Literature Review

Many past studies have reported on the variation of emission factors with average vehicle speed. The largest EFs for CO and other pollutants tend to occur at speeds of less than 20 mph because of inefficient engine operation primarily due to stop/start activity and frequent idling/acceleration. CO_2 emissions are linked directly to fuel consumption, so CO_2 emissions per mile go up at very low or very high speeds. Knowledge of traffic-flow patterns is relevant because local pollutant concentrations (more important for CO and PM; not as important for CO_2) are directly proportional to vehicle numbers and their characteristics (Bogo et al., 2001). Marsden et al. (2001) demonstrated an approach in microscopic traffic modeling for CO emissions based on vehicle speed and classification using vehicle acceleration, deceleration, cruising and idle inputs, enriched acceleration, state of repair of the vehicle emission control system, and type of engine. They showed that vehicle-exhaust emissions depend strongly on the fuel-to-air ratio. Sturm et al. (1998) described three approaches of compiling emission inventories based on "actual driving behavior," "specific streets," and "vehicle-miles traveled" (VMT). Among the parameters considered were local climate conditions and topography.

A study by Hallmark et al. (2002) found that driving patterns (e.g., speeds) at different intersections are significantly influenced by queue position, downstream and upstream lane volume, incidents, percent of heavy vehicles, and posted link speed. Emissions also vary with respect to drivers' attitude, experience, gender, physical condition, and age. Aggressive driving increases emissions compared to normal driving (De Vlieger et al., 2000). Sierra Research found that most drivers spend about 2% of total driving time in aggressive mode, which contributes about 40% of total emissions (Samuel et al., 2002).

Nesamani et al. (2007) proposed an intermediate model component that can provide better estimates of link speeds by considering a set of emission-specific characteristics (ESC) for each link. The intermediate model was developed using multiple linear regression and evaluated using a microscopic traffic simulation model. The evaluation results showed that the proposed emission estimation method performed better than current practice and was capable of estimating time-dependent emissions if traffic sensor data are available as model input.

Chu and Meyer (2009) described an analysis that utilized the U.S. EPA MOBILE6.2 vehicle emissions modeling software to identify freeway locations with large pollutant emissions and estimated the changes in emission associated with truck-only toll (TOT) lanes. Emissions including hydrocarbon (HC), carbon monoxide (CO), nitrogen oxide (NOx), and CO_2 were estimated by emission factors associated with various vehicle types and average speeds. The CO_2 calculation was limited due to lack of sensitivity in the model to speed variation, which was one of the benefits of the implementation of TOT lanes. The change in vehicle speeds was applied to estimate the change in fuel consumption and CO_2 emissions. The results showed that voluntary and mandatory use of TOT lanes would reduce total CO_2 emissions on all freeway lanes by 62%.

In an effort by Int Panis et al. (2011) to determine PM, NOx, and CO_2 emission reductions from speed management policies in Europe, they examined the impact on urban versus highway traffic with different modeling approaches; microscopic (VeTESS-tool) versus macroscopic (COPERT). Results indicated that emissions of most classic pollutants do not rise or fall dramatically. The effects of specific speed reduction schemes on PM emissions from trucks were ambiguous, but lower maximum speed (e.g., 55–65 mph) for trucks consistently resulted in lower fuel consumption and in lower emissions of CO_2.

In an earlier attempt by Int Panis et al. (2006) to model instantaneous traffic emissions and the influence of traffic speed limits, they concluded that the speed management impact on vehicle emissions is complex. The frequent acceleration and deceleration movements in the network may significantly reduce the benefits of changing the overall average speed. The conclusion from that study was that active speed management had no significant impact on total pollutant emissions.

Boriboonsomsin and Barth (2009) evaluated the effect of road grade on vehicle fuel consumption (and thus carbon dioxide emissions). The real-world experimental results showed that road grade does have significant effects on the fuel economy of light-duty vehicles both at the roadway link level and at the route level.

Papson et al. (2012) integrated SYNCHRO with MOVES and calculated emissions at congested and uncongested intersections using a time-in-mode (TIM) methodology that combines emission factors for each activity mode (i.e., acceleration, deceleration, cruise, idle) with a calculation of the total vehicle time spent in that mode. They demonstrated the contribution of each activity mode to intersection emissions and suggested opportunities for control strategies with the potential to affect intersection emissions.

Xie et al. (2011) integrated MOVES and the PARAMICS microscopic traffic simulation tool to evaluate the environmental impacts of three alternative transportation fuels—electricity, ethanol, and compressed natural gas—and to estimate the daily fuel savings and emission reduction of alternative fueled vehicles on the road network.

From the literature, it is clear that the type of analysis and the level of detail utilized (macroscopic or microscopic) to calculate traffic emissions affect the results extensively, as well as the studied factors such as the speed, percent heavy-duty trucks, and total number of vehicles. Furthermore, it is noted that research into CO_2 emissions is still in its infancy, especially when compared to other pollutant emissions. Finally, few studies were found to integrate the latest emission simulation model, MOVES2010, with a microscopic traffic simulation model. This paper addresses some of those shortcomings.

VISSIM Input/Output Data

VISSIM 5.3 is the microscopic, time-step and behavior-based traffic simulation model used in this study. The program can analyze traffic operations under constraints such as lane configuration, traffic composition, speed limits, traffic signals, and time of day, thus making it a useful tool for the evaluation of various alternatives.

The subject test bed in this study is a 10-mile stretch of Interstate 4 (I-4) in the Orlando, FL, downtown area. I-4 is an urban limited-access highway, a six-lane (6L) divided east–west transportation corridor serving commuters and commercial and recreational traffic. The freeway section included 11 links (9 of the segments are approximately 1 mile in length, including horizontal curves; the first and last links are 0.5 mile each). There were five on-ramps and five off- ramps, as shown in Figure 1. Traffic composition was set at 60% passenger cars (light-duty gasoline vehicles, LDGV), 37% passenger trucks (light-duty gasoline trucks, LDGT), and 3% heavy-duty diesel trucks (HDDV), as obtained from Florida Department of Transportation (FDOT) traffic information. The study period encompassed the eastbound evening peak hour from 5:00 to 6:00 p.m., which carries more than 6,000 vehicles per hour. The speed limits on the study corridor over the 10-mile section during the peak hour are from 30 to 40 mph as part of a variable speed limit (VSL) safety program. Therefore, VISSIM input volumes were assigned a speed distribution based around the posted speed limits. Roadway links were coded with 0% gradient, as nominal grade changes exist on the study corridor.

VISSIM currently does not have an integrated emissions model for North America. Higher level emissions statistics are available only via node evaluation. However, the VISSIM model generates a significant amount of output data detailing each vehicle's performance within the network, data that are critical for calculating air pollutant emissions. These details include second-by-second speed-acceleration profiles, network characteristics, and other vehicle parameters.

For this study, three types of output data were generated from VISSIM runs to correspond with vehicle characterization inputs within MOVES; a fourth VISSIM output was used in the hand calculation method. The first output included link-average speeds during the entire peak hour; the second output was a set of link-instantaneous speeds but on a second-by-second basis; and the third output included vehicle trajectory data: length, speed, acceleration, weight, location, and grade, on a second-by-second basis as shown in Table 1. The fourth output included an overall average speed and volume during the entire hour. All of the inputs required for MOVES emissions model were

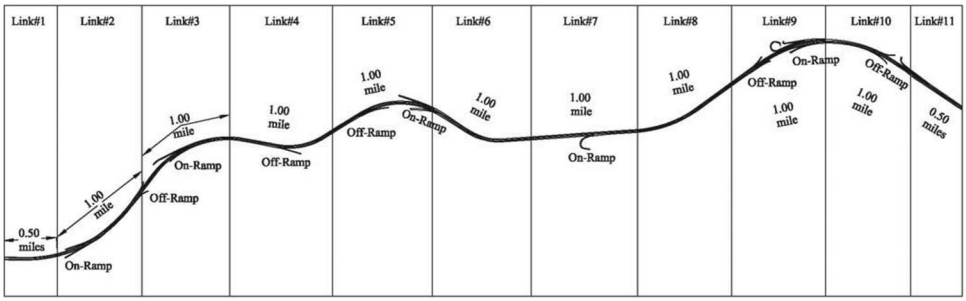

Figure 1. Urban limited-access highway network (I-4 downtown corridor).

Table 1. Excerpt from VISSIM.fzp file showing vehicle trajectory data

t (sec)	Link number (no.)	VehLength (ft)	VehNr (no.)	Type (no.)	Weight (mt)	a (ft/sec2)	V (mph)	DistX (ft)	WorldX (X)	WorldY (Y)	Grade (%)
60	1	14.4	215	100	0.8	0.82	27.42	176	–7816.74	–15425.6	0
60	1	14.9	207	100	1	–0.99	28.14	247	–7795.91	–15425.9	0
60	1	13.5	201	100	1.6	–0.69	26.43	297	–7779.42	–15426.1	0
60	1	15.1	195	100	1.8	–0.93	24.96	350	–7763.16	–15426.4	0
60	1	14.4	190	100	1.4	–1.35	23.25	401	–7747.78	–15426.6	0
60	1	14.4	185	100	1.7	–1.66	21.2	449	–7733.25	–15426.8	0
60	1	14.4	181	100	0.8	–1.39	18.97	499	–7718.97	–15427	0
60	1	15.6	178	100	1.1	–0.9	16.94	544	–7705.68	–15427.1	0
60	1	15.6	172	100	1.6	1.39	15.69	580	–7693.38	–15427.3	0
60	1	14.4	164	100	0.9	6.31	18.42	629	–7679.81	–15427.5	0
60	1	13.5	162	100	1.2	4.24	23.51	672	–7665	–15427.7	0
60	1	15.6	156	100	1.2	3.35	26.89	734	–7647.09	–15427.9	0
60	1	15.6	153	100	1	2.98	29.54	799	–7627.38	–15428.2	0
60	1	13.5	147	100	1.7	2.97	31.87	863	–7607.06	–15428.5	0

generated from VISSIM. It should be noted that each output was used in a different type of analysis.

MOVES Project-Level Data

MOVES can be used to estimate national-, state-, and county-level inventories of criteria air pollutants, greenhouse gas emissions, and some mobile source air toxics from highway vehicles. The MOVES model is different from previous U.S. EPA mobile source emissions models in that it was deliberately designed to work with databases that allow and facilitate the import of data specific to a user's unique needs (U.S. EPA, 2010a).

The U.S. EPA released MOVES2010a to account for emissions under new car and light truck energy and greenhouse gas standards. It incorporates new car and light truck greenhouse gas emissions standards affecting model year 2012 and later (published May 7, 2010) and updates effects of corporate average fuel economy (CAFE) standards affecting model years 2008–2011. The MOVES model includes a "default" database that summarizes relevant emission information for the entire United States. The data for this database come from many sources, including U.S. EPA research studies, Census Bureau Vehicle Surveys, Federal Highway Administration (FHWA) travel data, and other federal, state, local, industry, and academic sources (U.S. EPA, 2010a).

As mentioned earlier, the output from the VISSIM model was used as input into the MOVES model. For MOVES, the first input step is to create a project-level database where imported data are stored. Input files include meteorology data, traffic composition and percentage of trucks, length, volume, average speeds and grade, distribution of vehicles age, operating mode distribution for running emissions, link drive schedules, and fuel information (gasoline, diesel). A summary of MOVES project-level parameters used in this study can be seen in Table 2.

Vehicle Activity Characterization

Average speed, link drive schedules, and operating mode approaches

Selection of vehicle speeds and volumes on network links is a complex process due to the fundamental relationship between the volume and speed. The recommended approach for estimating average speeds and volumes is to post process the output from a traffic model (U.S. EPA and FHWA, 2010a, 2010b). Estimating vehicle emissions based on second-by-second vehicle operation can be achieved by integrating microscopic traffic simulation models along with an emissions model to obtain accurate results. Therefore, the simulated vehicle driving cycle output data from VISSIM was input into the MOVES model based on the already-mentioned project-level traffic conditions to calculate CO, NOx, PM, and CO_2 emissions. As mentioned earlier, four approaches were used to estimate vehicle emissions for the hour. Three detailed estimation approaches were used, all of which used 1-mile subsections: average speeds (AVG), link drive schedules (LDS), and operating mode distributions (OPMODE). The MOVES operating mode distribution allows one to define the amount of travel time spent in various operating modes, including braking, idling, coasting, and cruising/accelerating within various speed ranges and at various ranges of vehicle specific power (VSP). The last approach was a simple hand calculation that estimated emissions from total VMT at one average speed for the whole 10-mile stretch just to illustrate the "old" method of creating a mobile source emission inventory. In all of the model runs, only the "running exhaust emissions" were modeled.

Use of the AVG approach forces MOVES to use built-in driving schedules based on predefined speed bins and an interpolation algorithm to produce a default operating mode distribution. On the other hand, in the LDS approach, all similarly performing vehicles are modeled on a second-by-second basis using instantaneous speeds along with the link grade to obtain

Table 2. Summary of project-level parameters

Location county	Orange County, Florida
Calendar year	2010
Month	November
Time	5:00 p.m. to 6:00 p.m. (1 hr)
Weekday/weekend	Weekday
Temperature	75° F
Humidity	70.0%
Roadway type	Urban restricted access—represents freeway urban road with three lanes in each direction
(%) Types of vehicles (source type)	60% Passenger cars–LDGV (21), 37% passenger trucks–LDGT (31), and 3% long-haul combination diesel trucks–HDDV (62)
Type of fuel	Gasoline for passenger cars (LDGV) and trucks (LDGT); diesel for heavy-duty diesel trucks (HDDV)
Roadway length (11 links, total)	Approx. 1 mile/link – Total of 10 miles
Link traffic volume	4000-6,500 vehicles per hour
Link truck traffic	3% Heavy-duty diesel trucks (HDDV)
Average road grade	0%
Link average speed	20–40 miles per hour
Pollutant process	Running exhaust emissions
Output	CO, NOx, PM2.5, PM10, and atmospheric CO_2

their speed profile. However, even with this great amount of activity detail, MOVES will convert it to an operating mode distribution based on its internal algorithms. In the third approach (OPMODE), all vehicle activity data from VISSIM are preprocessed to develop the simulated operating mode distribution on a second-by-second basis, and this is input directly into MOVES. Thus, the main differences among these three approaches lie in the distinctions among the representations of each operating mode distribution.

Vehicle specific power (VSP)

MOVES estimates emissions by calculating a weighted average of emissions by operating mode. For running exhaust emissions, the operating modes are defined by vehicle specific power or the related concept, scaled tractive power (STP). Both VSP and STP are calculated based on a vehicle's speed and acceleration, but they differ in how they are scaled. The VSP, as shown in eq 1, is used for light-duty vehicles (source types 11–32), while the STP, as shown in eq 2, is used for heavy-duty vehicles (source types 41–62) (U.S. EPA, 2010b).

$$VSP = \frac{Av}{M} + \frac{Bv^2}{M} + \frac{Cv^3}{M} + (\mathrm{a} + \mathrm{g}\sin\theta)v \qquad (1)$$

$$STP = \frac{Av + Bv^2 + Cv^3 + Mv\mathrm{a}}{f_{scale}} \qquad (2)$$

where *VSP* is the vehicle specific power (kw/ton), *STP* the scaled tractive power (kw/ton), *M* the vehicle mass (metric tons), *A* the rolling term A (kw-s/m), *B* the rotating term B (kw-s^2/m^2), *C* the aerodynamic drag term C (kw-s^3/m^3), *v* the instantaneous vehicle velocity (m/s), a the instantaneous vehicle acceleration (m/s^2), θ the road grade (angle), and f the fixed mass factor.

Since "running" activity has modes that are distinguished by their VSP and instantaneous speed, the operating mode distribution generator (OMDG) classifies vehicle operating modes into different bins associated with vehicle specific power and speed, and develops mode distributions based on predefined driving schedules. The MOVES emission rates are a direct function of VSP, a measure that has been shown to have a better correlation with emissions than average vehicle speeds (U.S. EPA, 2002), and users can input locally specific VSP distributions based on the exclusive characteristics of the modeled system. VSP represents the power demand placed on a vehicle when the vehicle operates in various modes and at various speeds. In other words, the operating mode is a measure of the state of the vehicle's engine at that particular moment. This function produces operating mode fractions for each bin, which are used as one of several inputs for computing base emission rates.

VISSIM/MOVES Integration Software (VIMIS)

In order to develop project-specific VSP using the preceding equations and to define their explicit operating modes, VIMIS, a custom software package, was developed to integrate between VISSIM and MOVES and to facilitate the conversion process of VISSIM files into MOVES files. The output of the simulation run, as shown in Table 1, is a vehicle trajectory file that, for every second of the simulation, indicates each vehicle mass (M) and the

instantaneous speed (v) and acceleration (a) of every vehicle in the network. The remaining parameters are the road load coefficients (rolling, rotating, and drag) and the fixed mass factors for each source type. The road load coefficients (A, B, and C) are calculated from the track load horsepower (TRLHP) equation, and the fixed mass factors are equivalent to the average running weight for the weight class associated with each source bin obtained from the Mobile Source Observation Database (MSOD). The final source mass, fixed mass factors, and the road load coefficients for all MOVES source types are listed in the source use type characteristics table (U.S. EPA, 2010b). VISSIM vehicle types of passenger cars, passenger trucks, and heavy duty trucks (100, 150, and 200) were mapped to MOVES source types (21, 31, and 62), respectively. Using the calculated VSP along with MOVES VSP-Speed bin structure, each vehicle is assigned an operating mode ID. Then the total amount of time spent in each operating mode is calculated in percentage for each source type used in the network. "OPMODE" is a VIMIS module that converts the trajectory output file from VISSIM into an operating mode distribution for input into MOVES. In most cases, when the output is set on a second-by-second basis, the file size can reach 10 gigabytes and cannot be accessed by a conventional program. The great advantage of this module is that it converts this 10-gigabyte file into a 300-kilobyte file, and in a MOVES input format containing all the necessary links to be analyzed, types of pollutants, and emission processes (running, extended idle, etc.) to be executed by MOVES that calculates emissions.

Since both speed and acceleration are available in the microsimulation output for every vehicle for every second of simulation, MOVES operating mode distributions based on VSP were computed only in the OPMODE vehicle activity characterization approach. This is thought to be a more accurate way of capturing driving cycle patterns when literally thousands of vehicles have their trajectories traced, as in simulation. Since grade was set at 0% in the simulation, the term for it falls out of the equation and is not used.

Emissions Results and Analysis

Table 3 provides a comparison of the results for CO, NOx, PM2.5, PM10, and CO_2 emissions (kg) when the MOVES analysis was conducted using the three simulation approaches. For the same 10-mile stretch of I-4, those three approaches resulted in CO_2 emission estimates as follows: 19,478 kg, 23,912 kg, and 25,866 kg from the LDS, OPMODE, and AVG approaches, respectively. By comparison, the hand calculation in the fourth approach gave 32,800 kg. In general, the AVG approach estimated higher total emissions than the OPMODE approach while the LDS approach estimated lower total emissions (see Figure 2). If indeed the OPMODE approach is the most accurate, the AVG approach resulted in overestimation of emissions while the LDS approach resulted in underestimation of emissions.

Figures 3a–3e explain in greater detail the differences between the three approaches, link by link, and show the greater variability in emissions from the OPMODE approach when compared with the AVG and the LDS approaches. This is attributed to the fact that average speeds generally omit detailed vehicle activity such as acceleration and deceleration, especially at small speed differentials. Furthermore, this variability increases at certain locations (links 1–3 and 6–8) and decreases at other locations (links 4–5 and 9–10). When examining the network, it is found that links 1 and 2 are considered as loading points on the network from the mainline as well as the on-ramp, while link 3 is a discharging location (off-ramp) that creates a weaving area for vehicles trying to enter the network and others leaving. Weaving areas cause excessive acceleration and deceleration, resulting in increased braking, deceleration, idling, and acceleration. Large fractions of vehicles spend a substantial amount of time operating in these modes of stop-and-go operation, which are characterized by relatively high vehicle specific power and low speeds. The same pattern was seen for links 6, 7, and 8. However, emissions are lower on links 6–8 due to the relatively longer weaving distance between the on-ramp and the off-ramp, resulting in a relatively smoother operation in addition to lower volumes compared to the volume and weaving distance on links 1–3. Figure 4 maps the "OPMODE approach" operating mode distribution in details for links 1, 2, and 10.

Furthermore, the results displayed in Table 3 enable us to evaluate the behavior of the studied pollutants with respect to each other. According to Figure 2b, there is an apparent increase in NOx emissions in all estimation approaches when compared to the fleet composition, contrary to the results for CO and CO_2. In other words, passenger gasoline trucks, which accounted for 37% of the vehicle fleet, generated higher emissions than passenger gasoline cars, which accounted for 60% of the vehicle fleet, while the heavy-duty diesel trucks, which accounted for 3% only, generated higher emissions than the passenger cars (60%) and the passenger trucks (37%). This is attributed to a combination of increased vehicle weight (and thus more engine loading) and the fact that diesel engines produce much more NOx than gasoline engines. On the other hand, Figures 2d and 2e showed no significant difference between PM2.5 and PM10. However, they showed pattern similar to that of the NOx pollutant with regard to diesel trucks. Since the diesel vehicles represented 3% of the traffic on the network, the amount of PM emitted, especially from the gasoline vehicles, was extremely low compared to the rest of the pollutants over the 10 mile section. Moreover, Figures 3a–3e showed that all pollutants have higher sensitivity to the OPMODE scenario than the AVG or LDS scenarios.

Table 4 addresses the effect of VMT along with the operating mode distribution on the CO, NOx, PM2.5, PM10, and CO_2 emissions on selected corridor links. These links were selected for comparison purposes. Figure 5 also displays the total emission rate per link based on the OPMODE scenario for CO, NOx, and CO_2. As shown in Table 4, emission rates (emissions per vehicle-mile) are the highest on link 1 when compared to the rest of the network links, although Figures 3a, 3b, and 3c seem to show otherwise. The difference lies in the distance traveled (link 1 was only one-half mile long). All parameters should have the

Table 3. MOVES predicted emissions by pollutant, source type, link, and vehicle activity characterization approach

		CO emissions (kg/hr)			NOx emissions (kg/hr)			CO_2 emissions (kg/hr)		
Source type	Link number	AVG	LDS	OPMODE	AVG	LDS	OPMODE	AVG	LDS	OPMODE
Passenger cars—gasoline (LDGV)	1	4.99	3.81	6.45	0.50	0.24	0.67	771	605	863
	2	9.41	7.00	11.44	1.00	0.56	1.15	1425	1094	1500
	3	9.24	7.22	11.63	0.97	0.56	1.17	1408	1106	1508
	4	8.33	6.66	8.49	0.97	0.59	0.85	1266	997	1167
	5	7.35	6.08	6.94	0.88	0.57	0.69	1126	905	987
	6	7.85	6.04	7.89	0.86	0.53	0.81	1178	904	1124
	7	8.01	6.15	8.27	0.86	0.49	0.87	1213	943	1189
	8	8.10	6.26	8.39	0.86	0.49	0.87	1231	967	1203
	9	6.41	5.16	6.32	0.75	0.47	0.63	977	779	884
	10	6.41	5.27	6.04	0.78	0.48	0.60	983	778	856
	11	2.98	2.44	2.86	0.36	0.23	0.29	457	363	401
Total (LDGV)		79.08	62.09	84.73	8.79	5.21	8.60	12035	9442	11682
Passenger trucks—gasoline (LDGT)	1	5.19	3.39	6.59	0.64	0.32	0.79	624	469	688
	2	9.98	7.79	11.60	1.31	0.88	1.39	1163	880	1189
	3	9.76	7.50	11.75	1.26	0.82	1.40	1146	871	1199
	4	9.15	7.03	8.63	1.30	0.82	1.08	1046	792	920
	5	8.20	6.32	7.10	1.20	0.76	0.91	936	714	775
	6	8.40	6.37	8.11	1.13	0.74	1.04	964	718	889
	7	8.50	6.23	8.51	1.12	0.69	1.10	990	742	943
	8	8.56	6.28	8.63	1.11	0.69	1.09	1003	758	956
	9	7.08	5.45	6.44	1.02	0.65	0.82	809	617	696
	10	7.17	5.46	6.18	1.05	0.64	0.79	818	614	672
	11	3.33	2.55	2.92	0.49	0.31	0.37	380	288	315
Total (LDGT)		85.33	64.37	86.46	11.64	7.32	10.78	9879	7463	9242
Heavy-duty diesel trucks (HDDV)	1	0.30	0.22	0.32	1.08	0.69	1.05	248	140	246
	2	0.55	0.48	0.51	2.09	1.41	1.65	487	299	378
	3	0.55	0.45	0.53	2.03	1.39	1.72	471	292	400
	4	0.45	0.41	0.40	1.75	1.31	1.25	400	283	280
	5	0.39	0.36	0.34	1.54	1.19	1.07	350	259	239
	6	0.45	0.37	0.40	1.79	1.18	1.28	418	254	289
	7	0.47	0.37	0.41	1.79	1.18	1.33	415	250	298
	8	0.48	0.38	0.45	1.79	1.20	1.49	415	252	338
	9	0.34	0.31	0.30	1.33	1.01	0.98	303	219	218
	10	0.34	0.31	0.30	1.34	1.03	0.95	306	222	210
	11	0.16	0.15	0.13	0.62	0.48	0.41	142	103	93
Total (HDDV)		4.48	3.81	4.08	17.16	12.08	13.19	3952	2573	2987
Total emissions		168.88	130.27	175.27	37.59	24.60	32.57	25866	19478	23912

		$PM_{2.5}$ emissions (kg/hr)			PM_{10} emissions (kg/hr)		
Source type	Link number	AVG	LDS	OPMODE	AVG	LDS	OPMODE
Passenger cars—gasoline (LDGV)	1	0.0070	0.0044	0.0109	0.0076	0.0048	0.0119
	2	0.0147	0.0115	0.0186	0.0159	0.0125	0.0202
	3	0.0140	0.0111	0.0202	0.0152	0.0121	0.0219
	4	0.0145	0.0087	0.0120	0.0157	0.0094	0.0130
	5	0.0132	0.0076	0.0088	0.0143	0.0082	0.0095
	6	0.0128	0.0079	0.0109	0.0140	0.0086	0.0118
	7	0.0125	0.0082	0.0121	0.0136	0.0089	0.0132
	8	0.0124	0.0085	0.0124	0.0135	0.0092	0.0134
	9	0.0112	0.0068	0.0084	0.0122	0.0074	0.0092
	10	0.0115	0.0064	0.0076	0.0125	0.0070	0.0082
	11	0.0054	0.0030	0.0037	0.0058	0.0033	0.0040

(*Continued*)

Table 3. (Cont.)

Source type	Link number	$PM_{2.5}$ emissions (kg/hr)			PM_{10} emissions (kg/hr)		
		AVG	LDS	OPMODE	AVG	LDS	OPMODE
Total (LDGV)		0.1293	0.0843	0.1256	0.1404	0.0915	0.1364
Passenger trucks—gasoline (LDGT)	1	0.0057	0.0032	0.0087	0.0062	0.0035	0.0095
	2	0.0118	0.0063	0.0142	0.0129	0.0069	0.0154
	3	0.0113	0.0067	0.0154	0.0123	0.0073	0.0167
	4	0.0118	0.0053	0.0081	0.0128	0.0058	0.0087
	5	0.0109	0.0048	0.0054	0.0118	0.0052	0.0059
	6	0.0103	0.0048	0.0075	0.0112	0.0053	0.0082
	7	0.0101	0.0051	0.0085	0.0110	0.0056	0.0092
	8	0.0100	0.0053	0.0088	0.0109	0.0058	0.0096
	9	0.0092	0.0042	0.0054	0.0100	0.0045	0.0059
	10	0.0095	0.0041	0.0046	0.0103	0.0044	0.0050
	11	0.0044	0.0019	0.0023	0.0048	0.0021	0.0025
Total (LDGT)		0.1051	0.0518	0.0889	0.1141	0.0563	0.0965
Heavy-duty diesel trucks (HDDV)	1	0.0633	0.0321	0.0612	0.0653	0.0331	0.0631
	2	0.1247	0.0785	0.0957	0.1286	0.0810	0.0987
	3	0.1210	0.0749	0.0996	0.1248	0.0772	0.1027
	4	0.0929	0.0674	0.0712	0.0958	0.0695	0.0734
	5	0.0786	0.0605	0.0600	0.0810	0.0624	0.0618
	6	0.1064	0.0607	0.0725	0.1097	0.0626	0.0747
	7	0.1063	0.0599	0.0730	0.1096	0.0618	0.0753
	8	0.1065	0.0604	0.0831	0.1098	0.0623	0.0857
	9	0.0690	0.0530	0.0538	0.0711	0.0547	0.0554
	10	0.0684	0.0518	0.0534	0.0705	0.0534	0.0550
	11	0.0318	0.0242	0.0227	0.0328	0.0250	0.0234
Total (HDDV)		0.9690	0.6236	0.7462	0.9989	0.6429	0.7692
Total emissions		1.2033	0.7597	0.9607	1.2534	0.7907	1.0022

same units for a fair comparison between them. By normalizing emissions by distance, it was found that link 1 has the highest emission rate (e.g., 583 g/veh-mile CO_2). Furthermore, Link 1 has a greater fraction of the passenger car activity (about 30%) in the braking, idling, and low speed coasting operating modes (0, 1, and 11), as well as 20% in cruise/acceleration modes (12–16) at lower speeds (1–25 mph), as shown in Figure 4a. Link 2 shows nearly similar operating mode distribution patterns but with lower percentages than link 1, especially in operating mode 11 (coasting), and had a lower emission rate (486 g/veh-mile CO_2). It should be noted that link 2 has 152 vehicles more than link 1. However, emission rates are lower, which is attributed to improved traffic operations compared to link 1. Link 10 has the smallest emission rates among the corridor links (362 g/veh-mile CO_2). A greater fraction of the vehicle activity is in operating modes 21–25 (moderate speed coasting and cruise/acceleration); here there are relatively higher speeds (25–50 mph) with almost 0% idling or braking and 11% coasting. It is concluded that increased braking, idling, and coasting at lower speeds, along with the consequent re-accelerating, described as acceleration events, have a significant impact on pollutant emission rates.

The OPMODE approach offers the most detail, and is, in the authors' view, the most precise and accurate approach to estimating emissions. The total emissions of each pollutant over the 10-mile roadway varied depending on the approach used. For example, as seen in Table 3a, NOx was estimated to be emitted at 37.59, 24.60, or 32.57 kg/hr using the AVG, LDS, or OPMODE approach, respectively. Using the OPMODE approach as the base for comparison, variations in emissions of each pollutant are shown in Table 5 as percent differences. Figure 6 provide a comparison of operating mode distributions of the three approaches (AVG, LDS, and OPMODE)" for links 1, 2, and 10, which support the results in Table 5. As can be seen, the AVG operating modes are generally higher than the LDS and the OPMODE operating modes, especially in the lower speed bins (0–25 mph) as well as the higher speed bins ($\geq$50 mph) that, theoretically, do not exist based on posted speed limits of 40 mph. However, this is attributed to the effect of speed averaging. On the other hand, the LDS operating modes are confined in one or two modes at the most due to the effect of speed profiles. In general, the AVG approach overestimated emissions while the LDS approach underestimated emissions. Some of the differences are substantial.

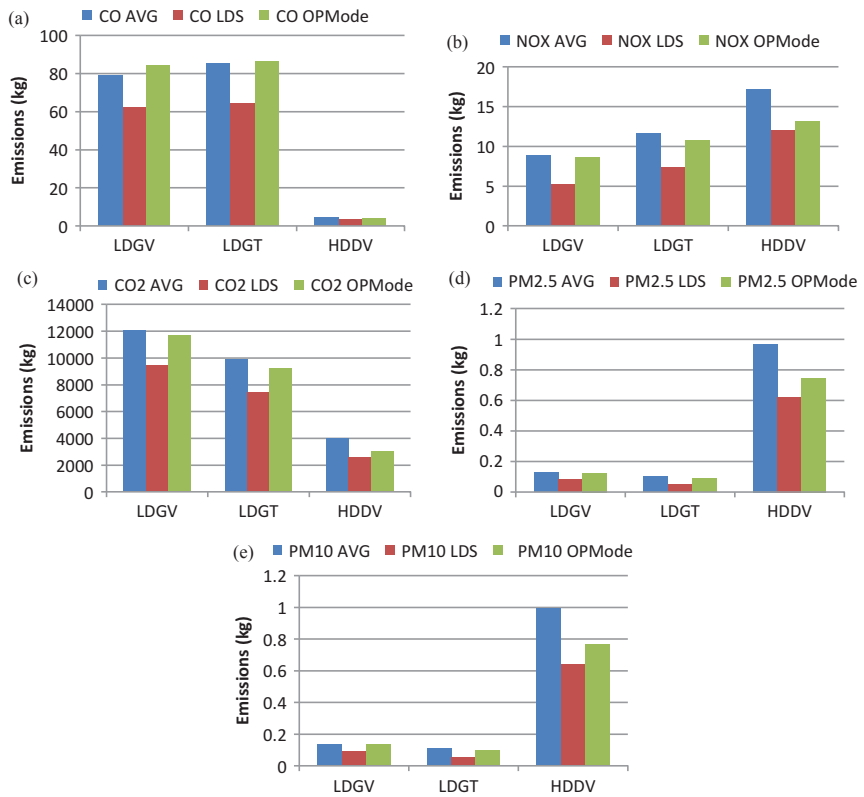

Figure 2. Total emissions by vehicle type and estimation approach for (a) CO, (b) NOx, (c) CO_2, (d) $PM_{2.5}$, and (e) PM_{10}. (Color figure available online.)

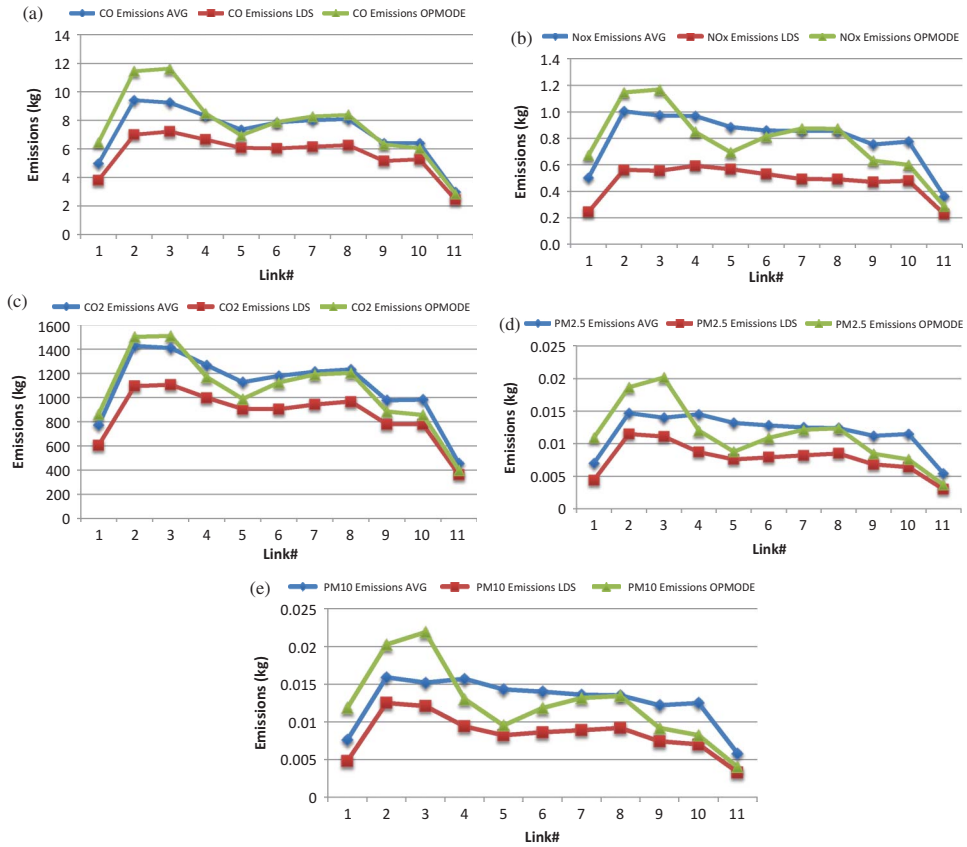

Figure 3. Emissions variation on network links for LDGV by estimation approach for (a) CO, (b) NOx, (c) CO_2, (d) $PM_{2.5}$, and (e) PM_{10}. (Color figure available online.)

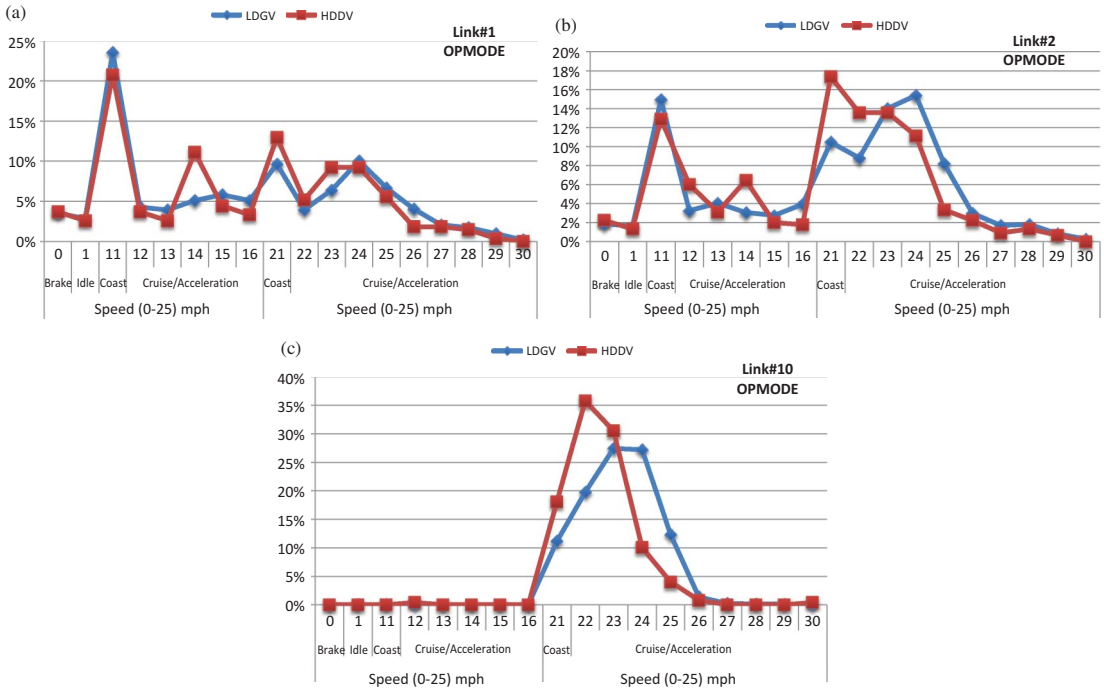

Figure 4. Link operating mode distribution by vehicle type on (a) link 1, (b) link 2, and (c) link 10. (Color figure available online.)

Conclusion

This paper presented a detailed examination of traffic-related key parameters, specifically traffic volume, speed, and truck percentage, using four different vehicle activity characterization approaches to capture the environmental impacts of vehicular travel on a limited access urban highway corridor in Orlando, Florida. The corridor was modeled using VISSIM and MOVES2010a. The VISSIM/MOVES integration module (VIMIS) was developed to estimate emissions derived from three detailed approaches characterizing vehicle activity, namel,y average speeds (AVG), link drive schedules (LDS), and operating mode distribution (OPMODE). The fourth (older) approach of hand calculation was shown for comparison purposes.

VISSIM outputs (link volumes, speeds, and acceleration/deceleration profiles) within each specified link in the network were combined with the MOVES model, which used VSP and instantaneous speeds to generate emission rates on a second-by-second basis. The same temporal resolution and level of detail in VISSIM and MOVES supported this combination of the two models. The OPMODE approach covered all the simulated combinations of instantaneous speeds and accelerations, and was used to develop accurate emissions for all desired driving patterns.

The results demonstrated that obtaining second-by-second vehicle operations from a traffic simulation model is essential to achieve the most accurate operating mode distributions and presumably the most accurate emissions estimates. Specifically, emission rates are found to be highly sensitive to the frequent acceleration events that occur at lower speeds, that is, frequent braking/coasting, idling (operating mode bins 0, 11, and 1, respectively) and re-accelerating. Emissions at any given moment (speed) on a link appear to be influenced by the power the vehicle used in getting to that speed from previous speed, expressed in acceleration rates. In the lower speed range (< 25 mph), the emission rates for VSP bins up to 12 kW/ton are actually higher than the emission rates from the same VSP bins in the higher speed range (> 25 mph) due to the effect of gear. In addition, results from VISSIM show that there are more frequent speed changes in the lower speed range, perhaps due to increased weaving and more aggressive driving. These two facts likely account for the higher emissions on links 1–3 compared with emissions on links 4, 5, and 10. Moreover, the use of an average speed often conceals the effects of acceleration/deceleration on emissions. Using AVG and LDS approaches resulted in overestimation and underestimation of emissions, respectively, when compared to the OPMODE approach.

In addition, the results of this study address previous conclusions (Int Panis et al., 2006) regarding evaluating speed management policies in Europe through modeling instantaneous traffic emissions and the influence of using an average speed approach. Int Panis et al. concluded that active speed management has no significant impact on pollutant emissions. They also concluded that "the analysis of the environmental impacts of any traffic management and control policies is a complex issue and requires detailed analysis of not only their impact on average speeds but also on other aspects of vehicle operation such as acceleration and deceleration" (Int Panis et al., 2006).

This study limited the pollutants to only CO_2, CO, PM2.5, PM10 and NOx; however, methods have been demonstrated that can be used for other mobile-source pollutants.

Table 4. Link emissions per vehicle per mile by source type

Link number	Source type	Emissions (kg)			Link volume	Link average speed (mph)	Link distance (miles)	Emissions (kg/veh-mile)		
		CO	NOx	CO_2				CO	NOx	CO_2
1	LDGV	6.45	0.67	863	6159	22.09	0.50	0.00209	0.00022	0.28015
	LDGT	6.59	0.79	688				0.00214	0.00026	0.22346
	HDDV	0.32	1.05	246				0.00010	0.00034	0.07980
Total		13.36	2.52	1797				0.00434	0.00082	0.58342
2	LDGV	11.44	1.15	1500	6311	27.31	1.001	0.00181	0.00018	0.23739
	LDGT	11.60	1.39	1189				0.00184	0.00022	0.18823
	HDDV	0.51	1.65	378				0.00008	0.00026	0.05988
Total		23.55	4.18	3067				0.00373	0.00066	0.48550
10	LDGV	6.04	0.60	856	4903	36.86	0.978	0.00126	0.00012	0.17846
	LDGT	6.18	0.79	672				0.00129	0.00016	0.14012
	HDDV	0.30	0.95	210				0.00006	0.00020	0.04385
Total		12.52	2.34	1738				0.00261	0.00049	0.36243

Link number	Source type	Emissions (kg)		Link volume	Link average speed (mph)	Link distance (miles)	Emissions (kg/veh-mile)	
		$PM_{2.5}$	PM_{10}				$PM_{2.5}$	PM_{10}
1	LDGV	0.0109	0.0119	6159	22.09	0.50	3.54E-06	3.86E-06
	LDGT	0.0087	0.0095				2.83E-06	3.08E-06
	HDDV	0.0612	0.0631				1.99E-05	2.05E-05
Total		0.0808	0.0845				2.62E-05	2.74E-05
2	LDGV	0.0186	0.0202	6311	27.31	1.001	2.94E-06	3.20E-06
	LDGT	0.0142	0.0154				2.25E-06	2.44E-06
	HDDV	0.0957	0.0987				1.51E-05	1.56E-05
Total		0.1285	0.1343				2.03E-05	2.13E-05
10	LDGV	0.0076	0.0082	4903	36.86	0.978	1.58E-06	1.71E-06
	LDGT	0.0046	0.0050				9.59E-07	1.04E-06
	HDDV	0.0534	0.0055				1.11E-05	1.15E-06
Total		0.0656	0.0187				1.37E-05	3.90E-06

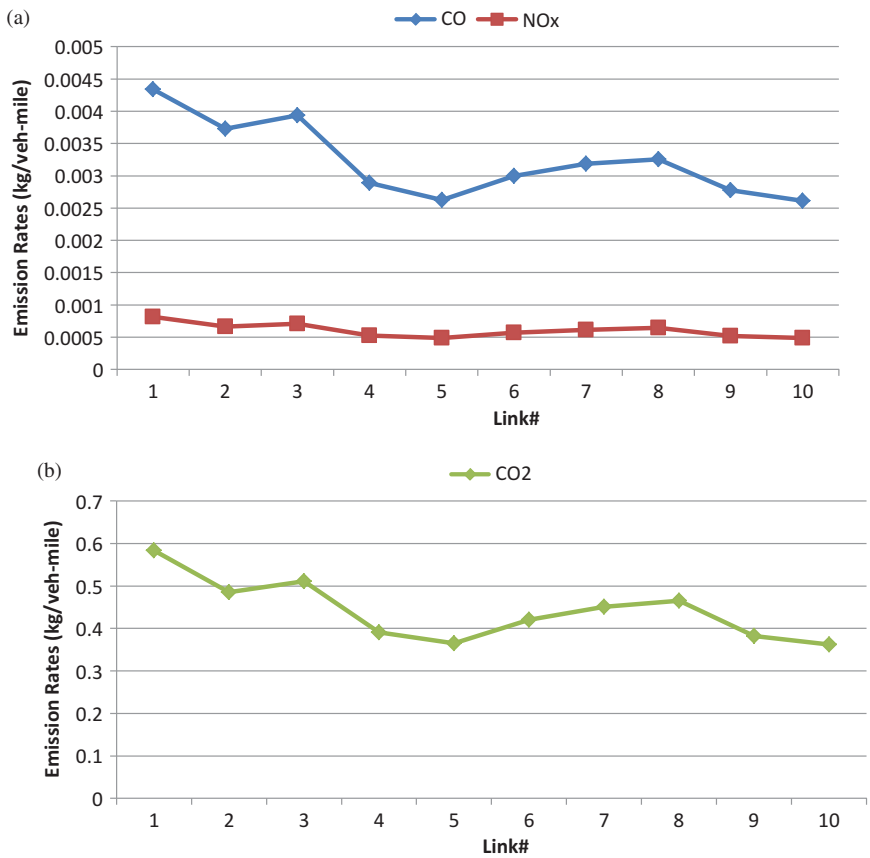

Figure 5. Total link emission rate (OPMODE scenario) for (a) CO and NOx and (b) CO_2. (Color figure available online.)

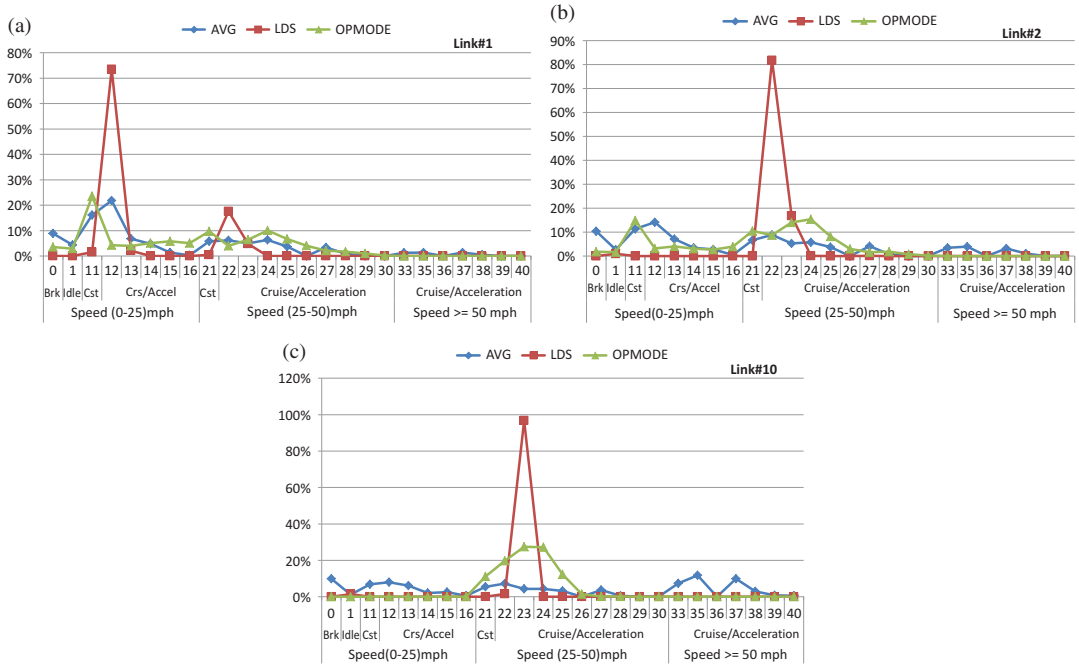

Figure 6. LDGV operating mode distribution comparison by estimation approach: (a) link 1, (b) link 2, and (c) link 10. (Color figure available online.)

Table 5. Percent difference compared to OPMODE approach

Approach	CO	NOx	CO_2	PM2.5	PM10
AVG	–3.65%	15.41%	8.17%	25.25%	25.06%
LDS	–25.67%	–24.47%	–18.54%	–20.92%	–21.10%

Microscopic traffic simulation models like VISSIM can produce second-by-second vehicle operating mode data, which can then be used directly in MOVES to obtain more accurate emissions. Furthermore, CO and PM dispersion modeling analyses, which are often required for roadway projects, can use the resulting spatially determinate EFs in roadway dispersion models such as CAL3QHC or AERMOD to predict concentrations of various pollutants near roadways, or in gridded ozone modeling.

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About the Authors

Hatem Abou-Senna, Ph.D., P.E. is a program director for transportation and air quality at the Center for Advanced Transportation Systems Simulations (CATSS) in the Civil, Environmental, and Construction Engineering Department (CECE) at the University of Central Florida (UCF).

Essam Radwan, Ph.D., P.E., F. ASCE is a professor of transportation engineering and the executive director of CATSS in the CECE Department at UCF.

Kurt Westerlund, E.I., is a Ph.D. candidate and graduate research assistant in the CECE Department at UCF.

C. David Cooper, Ph.D., P.E., QEP, is a professor of environmental engineering in the CECE Department at UCF.