A Report from the University of Vermont Transportation Research Center

# Evaluation of Transportation/Air Quality Model Improvements Based on TOTEMS On-road Driving Style and Tailpipe Emissions Data

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# Evaluation of Transportation/Air Quality Model Improvements Based on TOTEMS On-road Driving Style and Tailpipe Emissions Data

## University of Vermont Transportation Research Center

## June 30, 2014

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## Acknowledgements

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# 1.0 Overview

This final report summarizes two different efforts to model the real-world vehicle activity and tailpipe emissions data collected by the UVM Transportation Air Quality Laboratory for two model year 2010 Toyota Camry vehicles during on-road driving in Chittenden County, Vermont. The report includes two manuscripts that were presented at the annual Transportation Research Board meetings in Washington, DC in January 2013 and January 2014.

More information on the dataset used in these analyses can be found in the UVM Transportation Research Center report TRC #14-007 which describes the Total On-Board Tailpipe Emissions Measurement System (TOTEMS) sampling plan and instrumentation in detail.

# 2.0 Comparative Analysis of the EPA Operating Mode Generator with Real World Operating Mode Data

*Transportation Research Board (TRB) Paper 13-0387*

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## 2.1 Abstract

In June 2012, the Environmental Protection Agency (EPA) released the "Operating Mode Distribution Generator" (OMDG) a tool for developing an operating mode distribution as an input to the Motor Vehicle Emissions Simulator model (MOVES). The tool converts basic information about traffic operations – idle time, grade, and average speed – into an operating mode distribution. This tool is designed to make project-level analyses for CO and PM hot-spots easier to conduct with basic traffic activity data.

This paper compares the operating mode distributions obtained from this tool with those measured on a vehicle instrumented with the Total On-Board Tailpipe Emissions Measurement System (TOTEMS). TOTEMS generates a wealth of data, including a vehicle's speed, idle time, and link grade – all of the inputs necessary to run the OMDG. The comparison is made for 4 signalized intersections on an urban arterial in Burlington, Vermont.

This analysis shows that the OMDG, when compared to 31 test runs of an instrumented vehicle, was more accurate under circumstances of no to low grade and higher congestion (higher stop time). Estimation inaccuracies are most critical for specific operating modes -- for CO under high VSP conditions; for $PM_{10}$ under braking conditions (i.e. VSP <0).

This investigation has developed a method for quantitatively evaluating tools designed to simplify a mobile emissions analysis. Future work will include the development of models for estimating operating modes of a traffic stream using traffic microsimulation and highlighting those parameters that are most critical to calibrate for obtaining an accurate operating mode distribution estimate.

## 2.2 Introduction

The U.S. Environmental Protection Agency (EPA) has published guidance for performing "project-level" transportation conformity analysis of PM10, PM2.5, and CO "hot-spots" – sub-regional areas where local pollution concentrations might exceed National Ambient Air Quality Standards [1]. To quantify emissions impacts from hot-spots EPA requires use of the Motor Vehicle Emission Simulator (MOVES).Current regulations will require that MOVES be applied for "hotspot" analysis beginning in December 2012.

The development of MOVES creates a new era in mobile source modeling that brings with it some significant modeling challenges, particularly in developing accurate inputs. Key among the inputs for a project level analysis is the traffic activity data. MOVES provides three methods for supplying traffic activity data – average speeds, time-speed trajectories (link drive schedules), and operating mode distributions. However, prior research has concluded that, of these three methods, providing an operating mode distribution of the traffic stream results is the most direct method for taking advantage of the drive schedule data programmed into MOVES [2, 3, 4]. When using the other two approaches -- average speed or the link drive schedule -- MOVES translates the input data into an operating mode distribution resulting in some loss of accuracy.

There are many methods for estimating an operating mode distribution, including traffic microsimulation modeling. However, some of these methods can be quite sophisticated and, hence, costly. Further, as described below, there are questions raised in prior research regarding the suitability of traffic microsimulation for accurately replicating the operating modes of a traffic stream. For these reasons there is interest in developing simpler analytical methods for developing traffic activity data inputs to MOVES. Simpler analytical methods would be more affordable and easier to execute by agency staff tasked with performing or peer-reviewing a project-level analysis.

To advance the objective of having an analytically accessible traffic activity model, the EPA has developed the MOVES Operating Mode Distribution Generator (OMDG). The OMDG enables the analyst to input basic data on traffic operations – average speed of the vehicle stream, time spent idling (as a fraction of the total travel time), and average grade of the roadway – and obtain a corresponding operating mode distribution. Using the OMDG can greatly simplify the preparation of traffic activity data for input into MOVES. As the OMDG is a modeling tool that simplifies the approach, a key question relates to the accuracy of the OMDG's output. How much, if any, accuracy is sacrificed through the process of simplifying the traffic activity modeling?

This paper examines this question by comparing the operating mode distribution from a real-world instrumented vehicle with that obtained using the OMDG. We seek to understand how much CO and $PM_{10}$ emissions accuracy is sacrificed through simplifying the traffic activity input data with the OMDG.

## 2.3 Background

A number of studies have researched the preparation of traffic activity data as inputs to mobile source air quality models. Several of these have evaluated the use of microsimulation modeling for this purpose.

Chamberlin et al. [5,6] showed that microsimulation models could be used to develop traffic activity inputs to MOVES for analyzing the emissions impacts of traffic operational changes such as signal optimization or changes to an intersection control. The authors showed how microsimulation modeling could be used to prepare traffic activity data for each of the three input methods MOVES supports: average speed, link drive schedule, and operating mode distribution. The research concluded that operating mode distributions provide the most direct method of utilizing MOVES modal approach to emissions generation.

Other research has raised questions regarding the suitability of traffic microsimulation modeling for producing accurate traffic modal information. Hallmark and Guensler [7] compared

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the speed-acceleration distributions obtained from traffic activity data developed using the NETSIM miscrosimulation model with field data obtained with a laser range finder (LRF). The LRF data enabled the calculation of speed and acceleration for a sample of vehicles observed traversing a signalized intersection. The speed-acceleration distributions of sampled vehicles were calculated and compared against the distributions of similar vehicles modeled in the microsimulation. The analysis concluded that NETSIM, at default driver parameter inputs, does not adequately simulate instantaneous modal vehicle activity at intersection approaches. For mid-block operations, field data exhibited greater speed/acceleration variability than generated by NETSIM.

Viti et al. [8] estimated traffic stream operating modes at a signalized intersection using image processing. Their work compared the results of two microsimulation software packages and confirmed that the default driver acceleration parameters are not accurate representations of real-world operational activity data. Specifically, default microsimulation driver behavior parameters assume higher acceleration rates of unconstrained (non-following) vehicles, leading to an overestimation of emissions impacts.

Song et al. [9] reinforced this finding further when they evaluated the use of VISSIM to adequately replicate the operating modes of a real-world traffic stream obtained from an instrumented vehicle. They focused on vehicle specific power (VSP) as the most critical explanatory variable. The research team evaluated over 8,800 speed segments (>500,000 seconds of real-world speed data) to develop normal distributions of VSP by 2 mph speed bins. A simulation test bed was constructed in VISSIM and calibrated to average speed and flow. The simulation test bed indicated that microsimulation overestimated the fraction of vehicle flow in lower and higher VSP bins, resulting in significant errors in emissions estimates when compared to real-world data. The analysis went further to adjust 6 driver behavior parameters to determine whether the statistical fit between the real world and simulated VSP data could be improved. The authors concluded that traditional calibration methods could not improve the accuracy of replicating VSP distributions of real-world data.

In summary, foregoing research has evaluated the suitability of microsimulation modeling for generating traffic activity data inputs for MOVES. There is general concern that these methods may be beyond the capabilities of many agencies tasked with either conducting or peer reviewing a project-level analysis using MOVES. Furthermore,, much of the previous research questions the ability to calibrate microsimulation models to the operating modes of the real-world traffic stream.

To address these concerns, Papson et al. [10] developed a streamlined methodology which associates traffic activity with time spent in one of four "modes" – cruise, deceleration, acceleration, idle – using Webster's equations for time-distance relationships at intersections. The authors developed quantitative relationships to translate "time in mode" into emissions outputs for signalized intersections. This work represents one method for simplifying the traffic activity inputs to MOVES, basing an input operating mode distribution on a standard traffic engineeing analysis (level of service).

In one of the early research studies for establishing the process of conducting a project-level analysis using MOVES Pechan et al. [11] developed activity profiles for a number of facilities where a project-level emissions analysis may be required. These included freeway on-ramps, freeway-to-freeway interchanges, and signalized arterials. The authors developed default VSP profiles for these situations from which operating mode distributions could be estimated for input into MOVES.

EPA's newly released methodology – the MOVES Operating Mode Distribution Generator – is a further attempt to simplify the process of producing traffic activity inputs for MOVES. The OMDG is designed to simplify the approach to estimating operating modes based on average intersection approach speeds. In doing so, the OMDG is designed to provide a more

accurate estimate of a traffic stream's operating mode distribution than would be the case assuming a simple average speed for all approach traffic.

Acknowledging that any modeling exercise is a simplification of real world dynamics, the research presented in this paper seeks to identify the strengths and weaknesses of the OMDG tool for producing accurate traffic activity inputs to MOVES. The existence of highly detailed traffic activity data from an instrumented vehicle enables an analysis of the accuracy of the OMDG for replicating a real-world operating mode distribution given the relatively coarse traffic activity input data required by the OMDG.

## 2.4 Real-world Data

This research leverages part of a dataset developed at the University of Vermont Transportation Air Quality Laboratory using an on-board instrumentation package, TOTEMS, developed to quantify the following vehicle emissions and performance metrics at one second resolution while a test vehicle is driven on the real-world road network: tailpipe gas and particle pollutant emission rates, vehicle position, engine operating parameters, ambient environment and instrument conditions. All devices are powered by an on-board battery system to prevent additional loads on the vehicle engine. Details on the TOTEMS instrumentation can be found in previous work [12,13,14]. In this study, only vehicle activity and road grade data were used to address the research questions.

Vehicle position was measured using two GPS receivers mounted on the roof of the test vehicle. A Garmin GPS16-HVS receiver was used to provide primary location data and its Fugawi software synchronized computer clocks. A Geostats Geologger model DL-04, Version 2.4 served as a backup receiver. Speed and acceleration were determined based on vehicle speed data collected at >3 Hz by a Toyota TechStream OBD-II scantool. Scantool data were averaged to 1 Hz resolution to match that of the GPS receivers. Data were validated using range checking for individual scantool parameters; ArcGIS was used to remove erroneous locations outside a 25m route buffer.

Road grade was measured using the gyroscopic system of the Vermont Agency of Transportation ARAN van (Automated Road Analyzer; www.fugroroadware.com) at 0.002 mile spatial resolution. The test vehicle was a model year 2010 Toyota Camry conventional gasoline sedan driven by a single driver over a 32 mile driving route through Chittenden County Vermont. The vehicle weight with TOTEMS instruments, battery power system, driver and passenger was ~300 pounds over vehicle curb weight. Prior to data collection, the vehicle was driven on a 2.5-mile warm-up route so that engine coolant temperature was equal for cold and warm test dates over the study period (February 2010 to September 2011). Thirty-one repeated runs of the entire 32-mile route were used for this analysis. Temperature and relative humidity were logged with Onset HOBO loggers mounted both inside and outside the vehicle.

Vehicle specific power (VSP) was calculated from the measured vehicle speed, computed acceleration, and road grade joined to the vehicle's 1Hz lat/long GPS position using ESRI ArcMAP version 9 software.

$$VSP = n^{-1}\{av + bv^2 + cv^3 + mva + gmv \sin[\tan^{-1}(gG/100)])\}$$

where

| | |
|---|---|
| VSP | = vehicle specific power |
| n | = 1.4788 (fixed mass factor) |
| a | = 0.156461 |
| b | = 0.00200193 |
| c | = 0.000492646 |
| v | = speed in meters per second |

|   |   |
|---|---|
| a | = acceleration in meters per second per second |
| m | = 1.55001585 (vehicle mass in metric tons) |
| g | = 9.81 (acceleration of gravity) |
| G | = grade in percent |

## 2.5 Description of the Urban Arterial Test Bed

For this study a 0.70 mile portion of the 32-mile vehicle circuit was chosen as a test bed. This specific portion represents a signalized urban arterial corridor with moderate to high congestion. Hence, significant idling time can be encountered along its length, making it a good candidate for evaluating the OMDG.

The test bed (**Figure 2-1**) is in Burlington, Vermont, and begins just south of North Street and extends southward to south of Main Street. The corridor passes through five signalized intersections: Sherman Street, Pearl Street, Cherry Street, College Street, and Main Street, from north to south. Between North Street and Sherman Street, the corridor is one-way in the south bound direction and has two lanes. Between Sherman Street and Main Street the corridor has two lanes in each direction. For the purposes of this research the corridor has been divided into 6 segments of lengths ranging from 400 to 800 feet, five of which contain a signalized intersection (**Table 2-1**).

*The corridor is an urban arterial with a posted speed limit of 30 mph. Development the corridor is relatively dense and urban in nature, except for along the west side between Street and College Street, where there is a park. Between North Street and Pearl Street 1 and 2) the corridor is relatively level, but between Pearl Street and Main Street the corridor significant slope. On its 32-mile trial circuit, the TOTEMS vehicle progressed from north to from segments 1-6 sequentially.*

Table 2-**2** shows the key operating characteristics of the TOTEMS vehicle over each of the 6 Battery Street segments, providing the portion of the link travel time spent idling and the average vehicle speed. These two operating parameters are featured as they are inputs to the Operating Mode Distribution Generator.

Four of the six segments were selected for the comparative analysis described in this research. Segment 1 did not include a major intersection and thus would not include significant idling time, an essential input to the OMDG for this analysis. Segment 4 was also dropped from the analysis because its 6% grade was outside the grade thresholds supported by the OMDG [4].

Segments 2, 3, 5, and 6 are considered suitable for this comparative analysis for the following reasons:
- They incorporate a signalized intersection and, as a result, have a non-zero idling fraction.
- They include grade effects within the -5 to +5% thresholds supported by the OMDG.
- They have varying amounts of main-and side-street traffic providing variability in the traffic conditions encountered along each segment
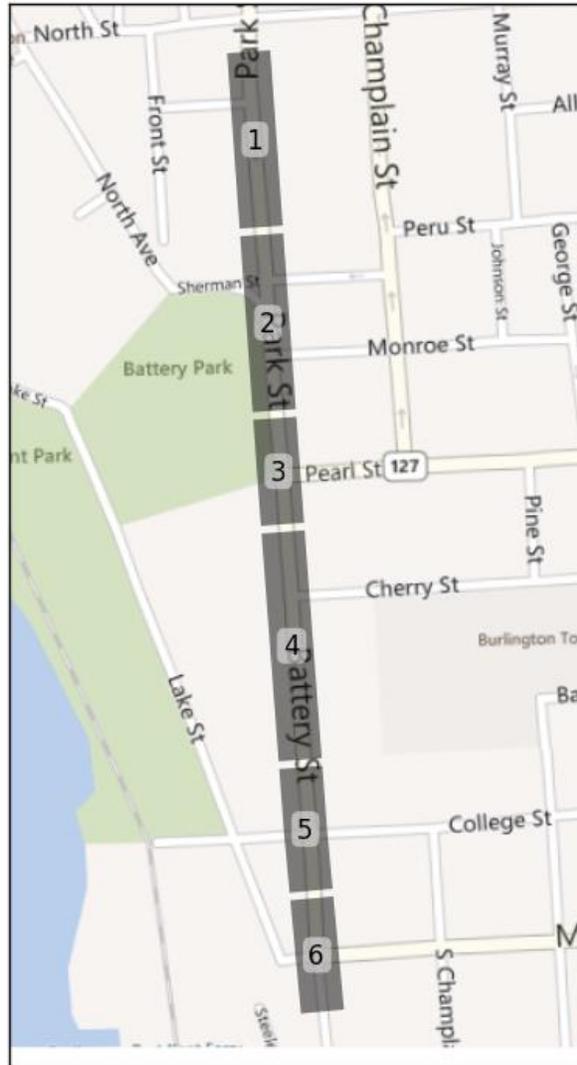
**Figure 2-1. Test Bed Urban Arterial, Battery Street in Burlington, Vermont, Showing Six Segments (four of which are used for the comparative analysis)**

**Table 2-1. Key Characteristics of the Battery Street Segments**

| Segment | Length (feet) | Grade (southbound) | Cross Street | Control | Major Street Daily Entering Vehicles | Cross Street Daily Entering Vehicles | Analyzed | Note |
|---|---|---|---|---|---|---|---|---|
| 1 | 650 | 0.3 | - | - | 4,300 | - | No | No major intersection |
| 2 | 650 | 0.5 | Sherman St | Signal | 9,000 | 5,000 | Yes | |
| 3 | 400 | -3.3 | Pearl St | Signal | 15,100 | 2,400 | Yes | |
| 4 | 800 | -6.2 | Cherry St | Signal | 16,100 | 1,700 | No | Grade outside of range of tool |
| 5 | 450 | -4.6 | College St | Signal | 13,900 | 2,800 | Yes | |
| 6 | 400 | -2.6 | Main St | Signal | 10,000 | 6,800 | Yes | |

**Table 2-2. TOTEMS Real-World Vehicle Operating Parameters by Street Segment**

| Segment | Portion Time Idling | Average Speed (mph) |
|---------|---------------------|---------------------|
| 1 | 0.000 | 16 |
| 2 | 0.400 | 11 |
| 3 | 0.100 | 21 |
| 4 | 0.025 | 28 |
| 5 | 0.055 | 19 |
| 6 | 0.320 | 11 |

## 2.6 Data Processing

The key question of this research is determining how well the simplifying analytics of the Operating Mode Distribution Generator can replicate operating modes from a real-world instrumented vehicle. It is assumed that some amount of data accuracy will be sacrificed for the greater simplicity in traffic activity inputs required by the OMDG. Thus, the key comparison is between the operating mode distributions produced by the OMDG with the real-world operating mode distribution of the TOTEMS vehicle. A second set of comparisons is made for hot-spot emissions – $PM_{10}$ and CO.

The OMDG has three main inputs: average speed, percent time idling, and average grade. These were calculated for each of the four segments using the data from the conventional TOTEMS vehicle, averaging across 31 separate runs through the Battery Street test bed. The OMDG input values for each of four segments were used to generate the operating mode distributions for each of the four segments 2, 3, 5, and 6. The operating mode distributions generated by the OMDG were then compared to the actual operating mode distributions calculated from the 31 TOTEMS vehicle trials for each of the four segments.

For the emissions analysis, these OMDG operating mode distributions and the TOTEMS, real-world operating mode distributions were run in MOVES assuming two year old vehicles of source type 21 (passenger vehicles). The MOVES emissions estimates were for Chittenden County, VT, during an 8:00 am hour in July of 2012. Estimates were for the running exhaust, tire wear, and brake wear emission processes.

## 2.7 Analysis of Results

**Operating Mode Distribution Comparison**. Operating mode distributions generated by OMDG for the TOTEMS data were in agreement with the OpMode frequencies computed directly from TOTEMS raw data for some for some segments and not others (**Figure 2-2**). The discrepancies between OMDG and mean TOTEMS OpModes could often be significant and outside a 95% confidence interval for the mean of the real-world data.

Many operating modes are not particularly significant from an emissions standpoint, while others are very significant given the specific emission factors associated with them within MOVES. For example, OpModes 0 and 11 showed large deviations from measured values for Segments 2, 3, 5 and 6. OpMode 21 differences were greatest for Segment 3. These OpModes which show frequency differences between OMDG and TOTEMS are expected to also result in differences in emission rates.

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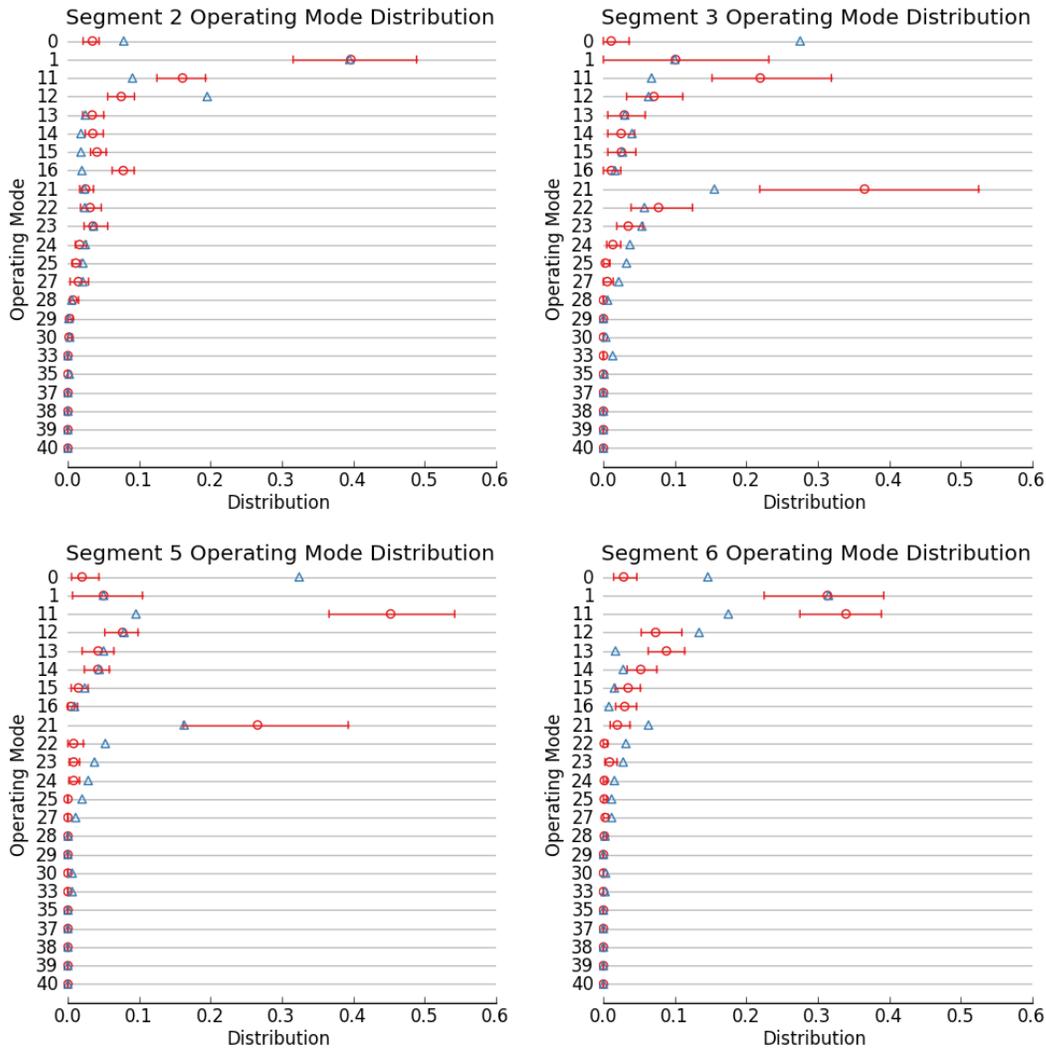
**Figure 2-2. Segment 2, 3, 5, 6 Operating Mode Distributions, OMDG (triangles) vs TOTEMS (circles)(note: the measurement band shows a 95% confidence interval of the mean of the TOTEMS vehicle over 31 trial runs)**

**Emission Rates**. The end goal of a project-level analysis is to estimate emissions, so an appropriate way to evaluate the performance of the OMDG is to compare MOVES emissions estimates based on the OMDG results to estimates based on the TOTEMS real-world operating mode distributions.

Looking at the overall emissions results by arterial segment (**Figure 2-3**), the analysis shows that the OMDG over-estimates CO emissions by about 30 percent or more for segments 3, 5, and 6, but roughly matches the TOTEMS estimates for segment 2. For $PM_{10}$, the OMDG and TOTEMS estimates are basically the same for segments 2,3,and 6, but the OMDG under-estimates for segment 5 by about 10%. The OMDG performs better for $PM_{10}$ (under-estimating by 10 percent for one segment), than for CO (over-estimating by 30 percent for three segments).

The difference in performance could be explained by the difference in variability of emission rates between $PM_{10}$ and CO. The raw emission rates by operating mode for $PM_{10}$ vary from about 0.3 to 2.4 grams per vehicle-hour (**Figure 2-4**). For CO, the emission rates by operating mode vary from about 0.3 to 800 grams per vehicle hour (**Figure 2-4**), making it more sensitive to errors in the operating mode distribution estimates. $PM_{10}$ emission factors by operating mode are

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less variable and, hence, more forgiving of errors in the operating mode distribution, resulting in better performance.

Another useful comparison to make is performance by segment within one pollutant type. For CO, the OMDG performed well for segment 2, and not as well for segments 3, 5 and 6 (**Figure 2-3**). To investigate the reasons for the difference in performance, we introduce the *weighted emission rate*, which is the product of the raw emission rate and operating mode distribution for a particular operating mode. The weighted emission rate indicates the amount of pollution in one vehicle-hour that can be attributed to a particular operating mode. The sum of all weighted emission rates across all operating modes is the overall emission rate for the vehicle-hour. Errors in the weighted emission rates (arising from errors in operating mode distribution) contribute to the error in the overall emission rate.

Investigating the weighted emission rates for CO shows that much of the error associated with segments 3, 5 and 6 can be attributed to over-estimating the distribution for operating mode 30 (**Figure 2-5**), which is the highest power-output operating mode for speeds between 25 and 50 mph, and has the highest emission rate of any operating mode (more than 800 grams per vehicle-hour – about three times higher than the second highest emission rate). With such a high emission rate, even small errors in estimating the distribution for operating mode 30 will have a large effect on the emissions estimates. In fact the absolute errors for operating mode 30 are small – less than one percent. But the magnifying effect of the large emission rate results in high emissions estimate errors.

The distribution for operating mode 30 is not as severely over-estimated for segment 2 as for the other segments (see **Figure 2-5**). One possible explanation is that the OMDG performs better for more moderate grades than for more severe grades. The MOVES default operating mode distributions (which are used by the OMDG) were developed to represent average conditions. As the traffic conditions being modeled depart from the average, the emissions estimates will become worse. Segment 2 has an average grade of 0.5 percent, but the segments 3,5 and 6 have grades of -3.3, -4.6, and -2.6 percent. It is possible that the more severe grades depart too much from average conditions to allow accurate emissions estimates.

For $PM_{10}$, the OMDG performed well for segment 2, 3, and 6 (**Figure 2-3**). However, looking at the weighted emission rates by operating mode (**Figure 2-6**) shows that for segments 3 and 6, the good fit results from relatively severe errors of opposite sign canceling each other out, which leaves only segment 2 as a truly good fit.

The main sources of error for $PM_{10}$ are operating modes 11 and 21, which are coasting modes for speed ranges 1-25 and 25-50 mph, respectively; and operating mode 0, which is braking. For segments 3, 5, and 6 braking is over-estimated and coasting is under-estimated (**Figure 2-6**). This may be due to the operational environment of the test bed. As the TOTEMS vehicle travels south along the 0.7 mile route portion, it enters and travels through a coordinated-signalized corridor. The first coordinated signal it encounters at Sherman Street in Segment 2; once the vehicle leaves the intersection at Sherman Street, it is unlikely to encounter a red light at a downstream intersection, which would result in less braking than for average conditions. On the other hand, arrivals at Sherman Street in Segment 2 are not coordinated, and so are more likely to encounter a red light, which may result in an operating mode distribution that is closer to the average.

Overall Emission Rates
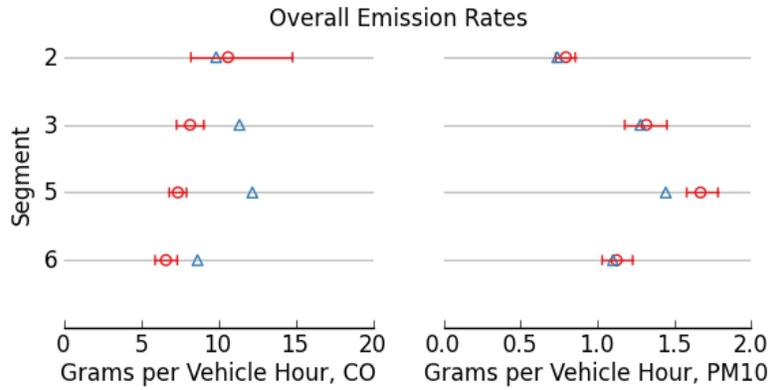


**Figure 2-3. Segment CO and PM$_{10}$ MOVES Emission Rates, OMDG (triangles) vs TOTEMS (circles).**
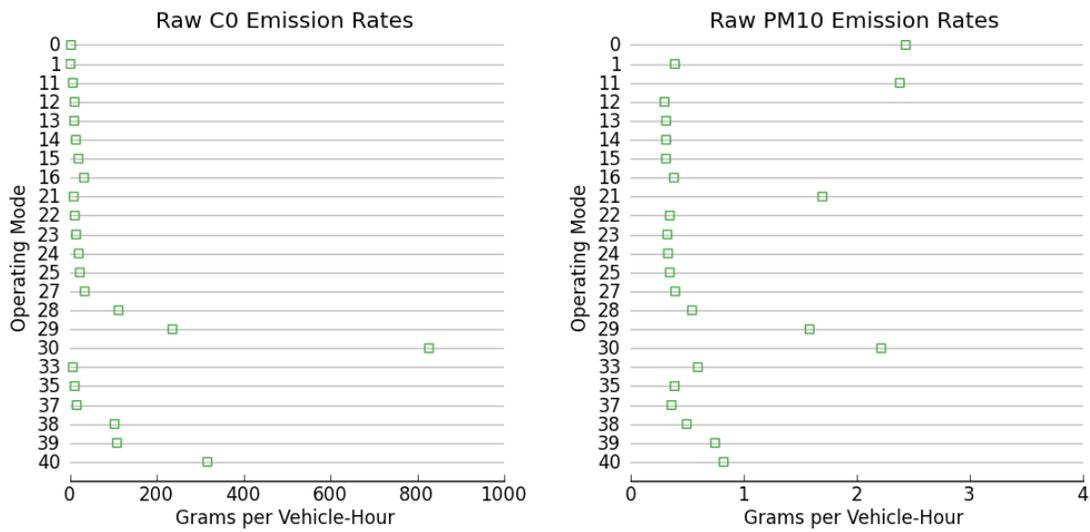


**Figure 2-4. Raw CO and PM10 MOVES Emission Rates by OpMode.**
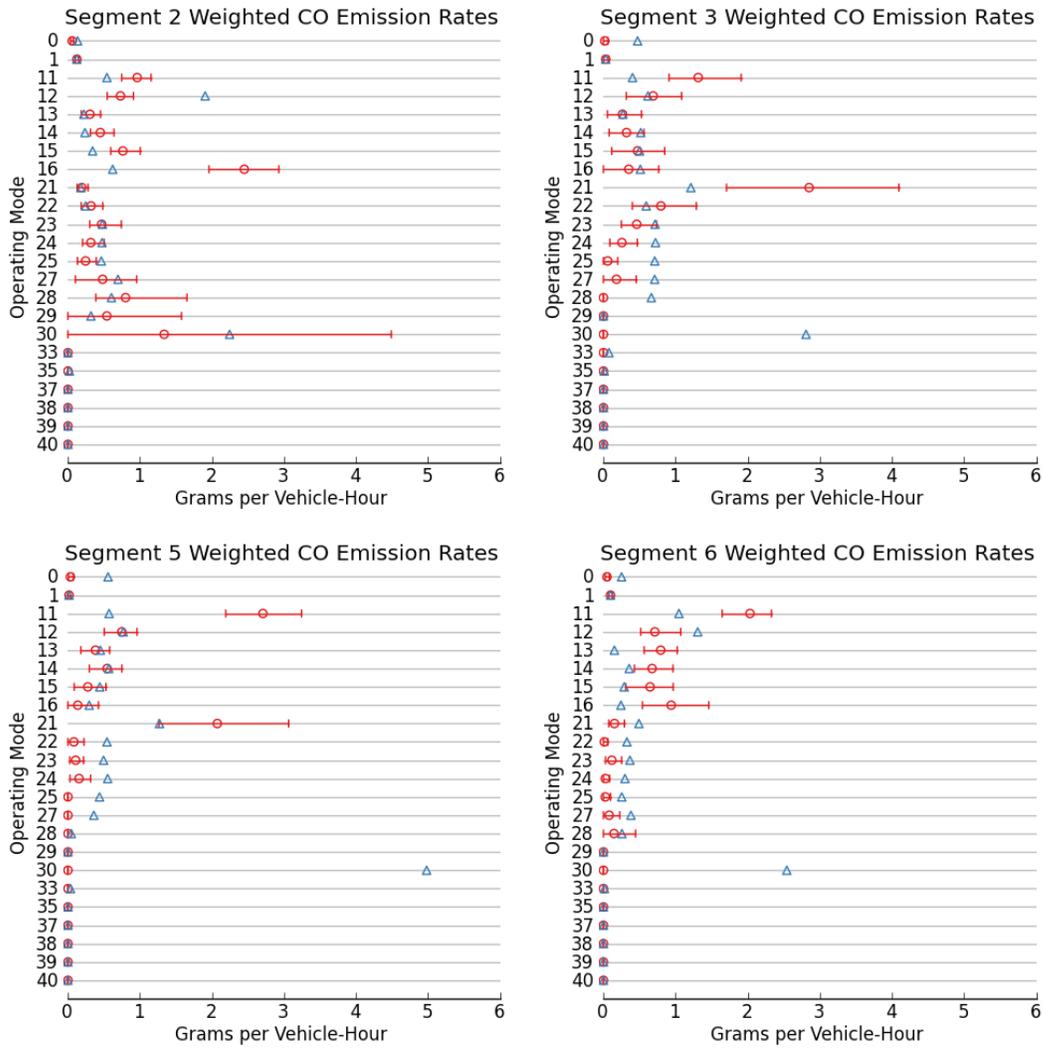
**Figure 2-5. Segment 2, 3, 5, 6 Weighted CO Emission Rates, OMDG (triangles) vs TOTEMS (circles)**
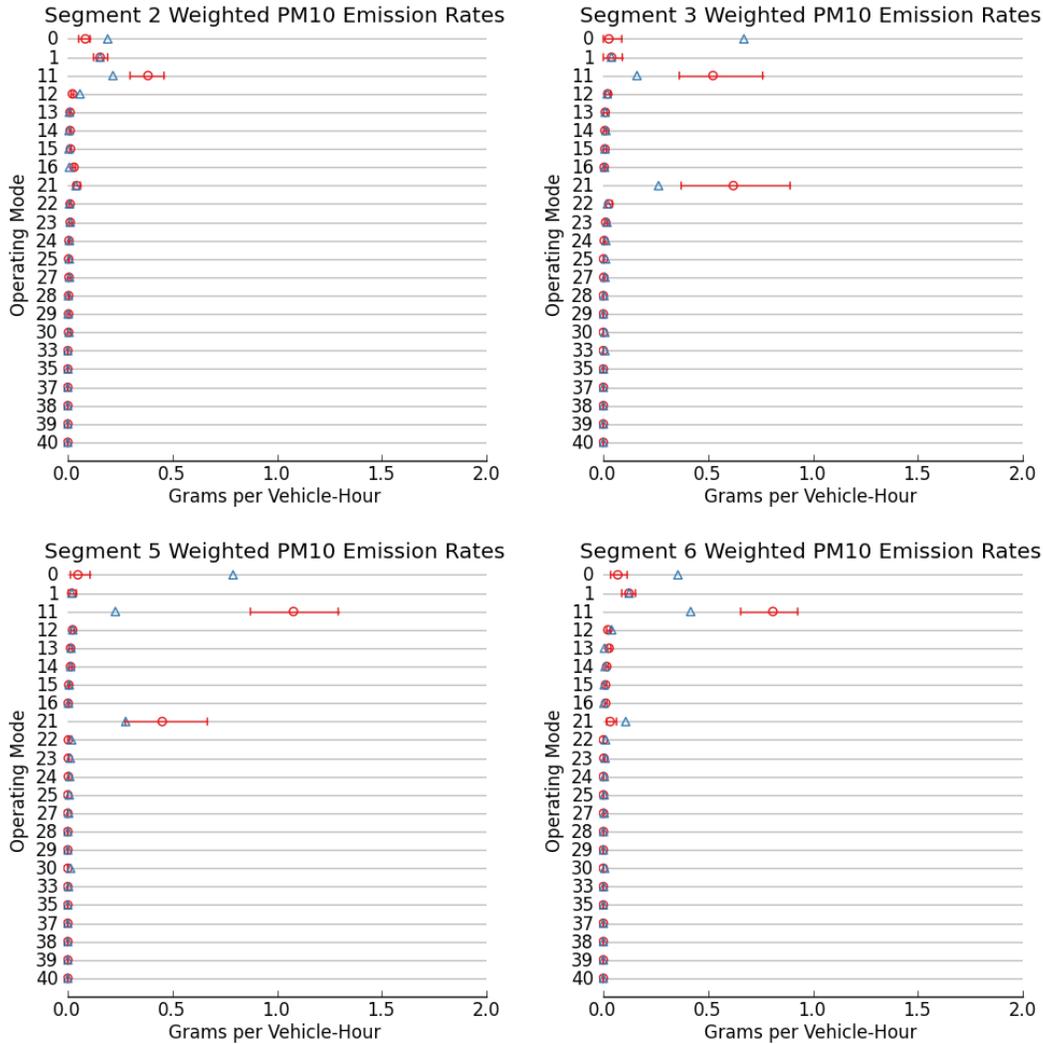
**Figure 2-6. Segment 2, 3, 5, 6 Weighted PM10 Emission Rates, OMDG (triangles) vs TOTEMS (circles)**

## 2.8 Conclusions

There is a desire to develop turnkey tools for developing traffic activity inputs to MOVES, particularly in light of current federal regulations requiring project-level hot spot analysis. Prior research has concluded that traffic microsimulation models are good candidates for developing these inputs. However, developing these models can be expensive and time consuming. Further, there are questions raised in the research regarding the applicability of default driver behavior assumptions embedded in microsimulation models, which can cause significant deviation of the simulated operating mode distribution from that of a real-world traffic stream.

In response, EPA has developed the Operating Mode Distribution Generator (OMDG), an Excel-based tool for estimating an operating mode distribution using coarser traffic activity inputs.

The research presented in this paper seeks to identify the strengths and limitations of the OMDG in replicating an operating mode distribution from real-world data obtained from an

instrumented vehicle driving along a signalized urban arterial. The research establishes the following:

1) For many operating modes the OMDG was a good predictor when compared with those obtained from the instrumented vehicle for all segments;

2) While no generally applicable rule can be distilled for where disagreement occurred, the data analysis points to specific operating modes where estimation error is more common and most critical in determining emissions impacts.

3) Estimation error for $PM_{10}$ stems from errors in operating mode distributions associated with braking (i.e. operating mode bin 1, 11, and 21). Due to the high $PM_{10}$ emission factors associated with these operating mode bins, small errors in estimating this operating mode will result in large errors in emissions estimates.

4) Estimation error for CO is associated with errors in the high acceleration operating modes (i.e. mode bins 29 and 30). Due to the high CO emission factors associated with these operating mode bins, even small errors in estimating this operating mode will result in large errors in emissions estimates.

5) Test bed arterial segments with higher grade had poorer results in estimating operating modes than the one segment (Segment 2) with a relatively flat grade.

# 3.0 Calibrating a Traffic Microsimulation Model to Real-World Operating Mode Distributions

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16

## 3.1 Abstract

This research seeks to understand how driver behavior parameters, as represented in one microsimulation package (TransModeler) can be modified to more closely match real-world vehicle operating characteristics for the purposes of emissions estimates with MOVES.

The calibration data for the research comes from a vehicle instrumented with the Total On-Board Tailpipe Emissions Measurement System (TOTEMS). TOTEMS generates a wealth of data, including a vehicle's second-by-second location, speed and acceleration. Data from 41 trials of a conventional gasoline vehicle is used as the basis to compare with microsimulation model output for two streets in Burlington, Vermont: 1) a signalized urban arterial; and, 2) a stop-controlled urban collector.

Adjustments to TransModeler car-following parameters could not adequately modify microsimulation vehicle operations to replicate the operational characteristics of the TOTEMS vehicles. However, adjustments to the free-flow model parameters were successful in more closely replicating real-world behavior. Specifically, default free-flow parameters governing the change in acceleration as a target link speed is approached were found to exaggerate driver aggressiveness.

Guidelines were developed for adjusting default microsimulation free-flow model parameters to more accurately reflect the operating mode of a real-world vehicle using tailpipe CO and $PM_{2.5}$ emission rates as comparison metrics. This research quantified the accuracy of a test bed microsimulation model when used for a mobile emissions analysis. For greater accuracy, analysts should be aware of the limitations of using the default free-flow microsimulation parameter values; the dependency of tailpipe emissions on acceleration rates suggest a need for improved microsimulation submodels and/or changes in default parameterizations to more accurately reflect real-world behavior.

## 3.2 Introduction

Transportation analysts need to provide accurate estimates of how highway improvements will affect emissions. The Environmental Protection Agency developed MOVES (Motor Vehicle Emission Simulator) to produce more accurate emissions estimates [15].

MOVES enables users to input vehicle activity as detailed second-by-second speed-acceleration trajectories. These trajectories are binned within MOVES into operating modes which, in turn, generate detailed emissions estimates. Coupled with traffic microsimulation, MOVES is potentially an excellent tool for detailed estimation of emissions changes associated with transportation improvements. Several recent research efforts have successfully linked output from traffic microsimulation models to MOVES [16-20]. However, significant questions remain as to whether key outputs from microsimulation models accurately represent real-world motorist behavior.

Microsimulation chiefly developed over the years as a tool for traffic operational analysis. As such, it has almost always been evaluated and calibrated against operational characteristics of the traffic stream, such as average speeds, throughput, queue lengths, etc. As long as the simulation reproduced these characteristics with sufficient realism, then the model was deemed to be "calibrated" [21].

However, MOVES depends on another characteristic of the vehicle stream that is usually ignored in model calibration efforts. This characteristic is the second-by-second speed-acceleration trajectory of each vehicle. Recent research has concluded that, while traffic microsimulation models can well calibrated to traffic operational characteristics, some model packages exaggerate driver acceleration behavior and, as a result, overestimate the resulting emissions. As such, the microsimulation-MOVES pairing would not be adequate for estimating vehicle emissions [22, 23].

On the other hand, if microsimulation model parameters could be adjusted to more accurately reflect real-world trajectories the two models combined could be a powerful tool for detailed analysis.

Motivated by the potential capabilities of the combined models, this study examines if and how microsimulation can be used to generate inputs to a MOVES emissions analysis. In particular, we want to discover the answers to the following question:

Can microsimulation models produce vehicle trajectories that appropriately reflect those of real-world drivers?

To answer this question, we deployed an instrumented probe vehicle to drive a test route in an urban area multiple times. A microsimulation model of the test route was built for the traffic conditions that the probe vehicle experienced, and was used to simulate the probe vehicle traveling the route. We then adjusted the simulation model parameters so that the simulated vehicle performance characteristics would match those of the actual probe vehicle. In this paper we detail this calibration process and present the main findings.

## 3.3 The MOVES Emissions Model

MOVES is EPA's air emissions calculator for mobile sources. MOVES supports regional air quality analysis, but also provides for more detailed analysis than the previous MOBILE family of emissions models due to an expanded set of "drive cycles", sequential records of acceleration, cruise, and deceleration behaviors associated with average travel speeds on specific roadway types. Within MOVES, drive cycles are further characterized by their

distribution of "operating modes", which represent a characteristic vehicle specific power (VSP) requirement associated with 3 speed ranges. In total there are 23 operating modes associated with emission rates for vehicles by type and age [24].

MOVES documentation states that the model "allows users to represent intersection traffic activity with a higher degree of sophistication compared to previous models [25], accounting for "speed and temperature variations", linked to emissions factors and processes obtained from extensive in-vehicle data collection. With this improved functionality, MOVES is potentially an excellent tool for conducting air quality assessments of operations-level changes such as intersection improvements. Indeed, as described above, EPA requires that MOVES be used to complete PM and CO hot-spot analysis [26]. In addition, it is expected that MOVES be used for conducting the air quality analysis associated with NEPA review of transportation projects.

## 3.4 The TransModeler Acceleration Model

TransModeler [12] is one of several commercial software packages that enable the construction of traffic microsimulation models. In TransModeler, normal vehicle acceleration is governed by two models: the free-flow model, and the car-following model. Each of these two models has a component for positive acceleration and a component for deceleration. Because acceleration calibration is more important for emissions estimation than deceleration calibration, we focus on calibrating the positive acceleration components of the two models (car-following and free-flow).

*Car-Following model*
For the car-following regime (defined for most vehicles as a time headway of less than 3.17 seconds) the acceleration is given by

$$\dot{V}_{i,j+1} = A^a \frac{V_{ij}^{B^a}}{D_{ij}^{\Gamma^a}} \left( V_{i-1,j} - V_{ij} \right) + \varepsilon_i^{CF} \qquad \text{[ii]}$$

where

$$
\begin{aligned}
\dot{V}_{i,j+1} &= \quad \text{the acceleration for vehicle } i \text{ at time } j + 1; \\
A^a, B^a, \Gamma^a &= \quad \text{car following parameters for acceleration;} \\
V_{ij} &= \quad \text{the speed of vehicle } i \text{ at time } j; \\
D_{ij} &= \quad \text{the distance between vehicle } i \text{ and its leading vehicle at} \\
& \qquad \text{time } j; \\
V_{i-1,j} &= \quad \text{the speed of vehicle } i\text{'s leading vehicle at time } j; \\
\varepsilon_i^{CF} &= \quad \text{car following variation parameter for vehicle } i \text{ (ft/s/s).}
\end{aligned}
$$

The parameters $A^a, B^a, \Gamma^a$ are global constants for all vehicles and all links and have default values of 2.81, -1.67, and -0.89, respectively. These parameters can be adjusted by the user.

The parameter $\varepsilon_i^{CF}$ is constant for one vehicle but can vary across vehicles. As vehicles enter the network they are assigned a value for this parameter randomly from a discrete distribution. The default values are 0, -0.1, and 0.1 with probabilities of 30%, 50%, and 20%, respectively.

*Free-flow model*

For the free-flow regime, the acceleration for vehicle *i* at time *j* is given by Equation i:

$$\dot{V}_{ij} = \alpha_i^a + \beta_i^a \left[ T^a\left(w_i/p_i, v_{ij}\right) - \frac{gG_{ij}}{100} \right] + \varepsilon_i^{FF} \qquad [i]$$

where

$$\dot{V}_{ij} = \quad \text{the acceleration of vehicle } i \text{ at time } j \text{ (ft/s/s);}$$
$$\alpha_i^a = \quad \text{additive acceleration parameter for vehicle } i \text{ (ft/s/s);}$$
$$\beta_i^a = \quad \text{multiplicative acceleration parameter for vehicle } i \text{ (unitless);}$$
$$T^a\left(w_i/p_i, v_{ij}\right) = \quad \text{global look-up table and interpolation function for acceleration for vehicle of weight } w_i, \text{(lbs), power } p_i \text{ (horsepower), and speed } v_{ij}\text{(mph) at time } j;$$
$$g = \quad \text{global constant representing the effect of grade on acceleration (ft/s/s);}$$
$$G_{ij} = \quad \text{roadway grade for vehicle } i \text{ at time } j \text{ (\%); and}$$
$$\varepsilon_i^{FF} = \quad \text{free-flow variation parameter for vehicle } i \text{ (ft/s/s).}$$

The free-flow model parameters $\alpha_i^a$, $\beta_i^a$, $\varepsilon_i^{FF}$, $w_i$, $p_i$ are all constant for one vehicle, but can vary from vehicle to vehicle. As vehicles enter the simulation they are randomly assigned values for these parameters using three user-defined discrete probability distributions. Two of the distributions give joint probabilities for pairs of parameters: $\alpha_i^a$ and $\beta_i^a$; and $w_i$ and $p_i$. The third distribution gives probabilities for a single parameter: $\varepsilon_i^{FF}$. Table gives the default probabilities for $\alpha_i^a$ and $\beta_i^a$ and $\varepsilon_i^{FF}$. The probability distribution for $w_i$ and $p_i$ is not presented here because it is almost always modified by the user to be different than the default. The lookup table for $T^a$ is given in Error! Reference source not found.**Table 3-1**. The function returns an acceleration value in feet per second per second (fpsps) using bilinear interpolation based on $v_{ij}$, and $w_i/p_i$.

The global constant $g$ is used to model the effect of grade on acceleration. This value should always be positive so that uphill grades predict lower magnitude positive accelerations than do downhill grades. This parameter is related to the acceleration of gravity, but it is not meant to model the effect of gravity. Rather, it is a parameter for a behavior model, not for a physical model. The default value is 30.5 (feet per second per second).

The free-flow model incorporates an acceleration model that is applied when the current speed is near the target roadway speed in order to avoid overshooting the target speed (email communication with Caliper, 2012). This model has an important impact on vehicle operating performance because it forces a rapid reduction in acceleration as the target speed is achieved.

**Table 3-1. Default Probability Distributions for Free-Flow Model Acceleration Parameters, and Default Lookup Table for Free-Flow Model Parameter $T^a$**

| Probability | $\alpha_i^a$ | $\beta_i^a$ | | Probability | $\varepsilon_i^{FF}$ | |
|:---:|:---:|:---:|:---:|:---:|:---:|:---:|
| 0.20 | 0.0 | 1.2 | | 0.30 | 0.0 | |
| 0.60 | 0.0 | 1.0 | | 0.50 | -0.1 | |
| 0.20 | 0.0 | 0.8 | | 0.20 | 0.1 | |

| $w_i/p_i$ | $v_{ij}$ | | | | | |
|:---:|:---:|:---:|:---:|:---:|:---:|:---:|
| | **<10** | **10-20** | **20-30** | **30-40** | **40-50** | **>50** |
| **25** | 9.2 | 9.2 | 7.9 | 7.2 | 6.2 | 5.6 |
| **30** | 7.9 | 7.9 | 6.6 | 5.9 | 5.2 | 4.6 |
| **35** | 6.9 | 6.9 | 5.6 | 4.9 | 4.3 | 3.9 |
| **100** | 3 | 3 | 2 | 1.6 | 1 | 0.7 |
| **201** | 1.6 | 1.6 | 1.3 | 0.7 | 0.7 | 0.3 |
| **299** | 1.3 | 1.3 | 1 | 0.7 | 0.3 | 0.3 |
| **399** | 1.3 | 1.3 | 1 | 0.3 | 0.3 | 0.3 |

## 3.5 Calibration Method

**Probe Vehicle Data**
This research leverages a dataset developed at the University of Vermont Transportation Air Quality Laboratory using an on-board instrumentation package, TOTEMS, developed to quantify the following vehicle emissions and performance metrics at one second resolution: tailpipe gas and particle pollutant emission rates, vehicle position, engine operating parameters, and ambient environment. All devices are powered by an on-board battery system to prevent additional loads on the vehicle engine. Details on the TOTEMS instrumentation can be found in previous work [28-30]. In this study, only vehicle activity and road grade data were used to address the research question.

Vehicle position was measured using two GPS receivers mounted on the roof of the test vehicle. A Garmin GPS16-HVS receiver was used to provide location data. Speed and acceleration were determined based on vehicle speed data collected at >3 Hz by a Toyota TechStream OBD-II scantool. Scantool data were averaged to 1 Hz resolution to match that of the GPS receivers. Data were validated using range checking for individual scantool parameters; ArcGIS was used to remove erroneous locations outside a 25m route buffer.

Road grade was measured using the gyroscopic system of the Vermont Agency of Transportation ARAN van (Automated Road Analyzer; www.fugroroadware.com) at 0.002 mile spatial resolution.

The test vehicle was a model year 2010 Toyota Camry conventional gasoline sedan driven by a single driver over a 32 mile driving route through Chittenden County Vermont. The total vehicle weight with TOTEMS instruments, driver and passenger was ~300 pounds over vehicle curb weight. Thirty-one repeated runs of a sort portion (Figure ) of a 32-mile route were used for this analysis (February 2010 to September 2011).

Vehicle specific power (VSP) was calculated from the measured vehicle speed, computed acceleration, and road grade joined to the vehicle's GPS position using ESRI ArcMAP version 9 software.

$$VSP = n^{-1}\{av + bv^2 + cv^3 + mva + gmv\sin[\tan^{-1}(gG/100)])\} \qquad [iii]$$

where

| | |
|---|---|
| VSP | = vehicle specific power (kW/metric ton) |
| n | = 1.4788 (fixed mass factor) |
| a= 0.156461 | |
| b | = 0.00200193 |
| c | = 0.000492646 |
| v | = speed in meters per second |
| a | = acceleration in meters per second per second |
| m | = 1.55001585 (vehicle mass in metric tons) |
| g | = 9.81 (acceleration of gravity) |
| G | = road grade in percent |
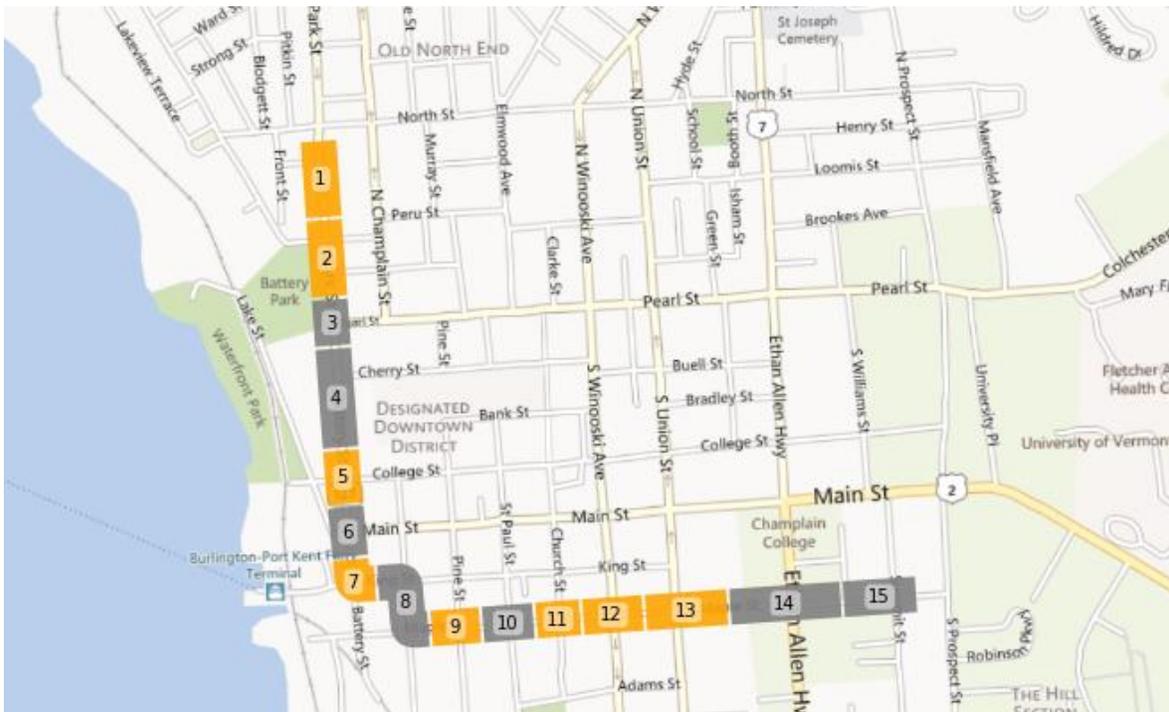


**Figure 3-1. The probe vehicle test route in Burlington VT. Road segments are identified by number and color indicates segments used for calibration [orange] or validation [grey]. The test bed is a short urban segment of a larger 31-mile route.**

**Traffic Microsimulation**

We built a microsimulation model of the test route using the TransModeler software package (version 3.0) to represent the traffic conditions encountered by the probe vehicle. The simulation was constructed to represent midday weekday conditions (and probe data from this time period only was used). To model the probe vehicle we added a special class of vehicles to the simulation. This class was defined to have weight and horsepower identical to the probe vehicle. Over the course of a 1 hour simulation, 20 simulated probe vehicles traversed the test route, departing every 3 minutes.

**Calibration Metric, Search Method, and Validation Method**
Model calibration was performed using a random sample of the 15 test route segments. Four segments were randomly selected from the signalized portion of the route (segments $1 - 8$), and four additional segments were randomly selected from the non-signalized portion (segments $9 - 15$), for a total of 8 model calibration segments. The calibration segments are 1, 2, 5, 7, 9, 11, 12 and 13. The remaining 7 segments are reserved to validate the model once calibration was completed.

To calibrate the model parameters, we used a global search approach. For each parameter of interest, we ran the simulation several times. For each simulation, the parameter value was chosen randomly from a pre-defined range around the default parameter value. For each simulation, the vehicle trajectories were saved along with the associated parameter values.

After all simulations were complete, the simulation results were grouped into bins defined by intervals of the value of the parameter of interest. For each bin, the MOVES operating mode distribution was calculated for the simulated probe vehicle for each test route segment. The operating mode distributions were used to calculate the emission rates (grams per vehicle-hour) for each segment and bin using MOVES.

Operating mode distributions were also calculated for each segment using the real-world TOTEMS probe data. These operating mode distributions were used to calculate emission rates for each segment using MOVES. To calibrate the model, we minimized the difference between the MOVES emissions rates based on the simulated activity versus the TOTEMS probe vehicle activity. To measure the difference, we used mean log relative error (MLRE), which is given by

$$\frac{1}{n}\sum_{all\ i}\left|log_{10}\left(\frac{r_{sim,i}}{r_{probe,i}}\right)\right| \qquad [iv]$$

where $n$ is the number of model test route segments, $i$ indexes the segments, $r_{sim,i}$ is the emission rate calculated from the simulation data, and $r_{probe,i}$ is the emission rate calculated using the TOTEMS activity data.

We evaluate model calibration using CO and $PM_{2.5}$. For each pollutant, the emissions rates are calculated in MOVES for the 1:00 pm hour in July 2011, for a one-year-old passenger car. For CO, the estimates include running emissions only. For PM2.5, the estimates include running emissions, tire wear, and brake wear emissions.

A total of three parameters were tested. The parameter $A^a$ was the single parameter tested from the car-following model. The other two parameters were $T^a$ and $g$ from the free-flow model. Each of these parameters was tested over a range of values across multiple simulations.

## 3.6 Calibration Results

**The car-following model**
The parameter $A^{\alpha}$ is a scaling multiplier for the car-following acceleration model. Increasing the value of this parameter (making it more positive) will increase the magnitude of acceleration. The default value for this parameter is 2.81. For calibration, the parameter value was allowed to vary between 0.703 and 11.2. The simulation was run 100 times. Simulation results were binned into 5 groups according to the parameter value used in each

simulation. The second group with values between 2.07 and 4.3 included the default value of 2.81. Each group included 20 simulations on average. The other groups covered parameter value ranges higher and lower than the default value. These other groups were used to test changes to the parameter value from the default value.

The emissions results show little sensitivity to $A^\alpha$. For both CO and PM$_{2.5}$, the worst MLRE is only seven percent greater than the best MLRE (**Figure 3-2**). Because the errors are not sensitive to $A^\alpha$, it was set at its default value of 2.81. The car-following model has 3 other parameters that were not tested because it is unlikely that the errors will be sensitive to these parameters if the errors are not sensitive to the multiplier ($A^a$) (see Equation ii).
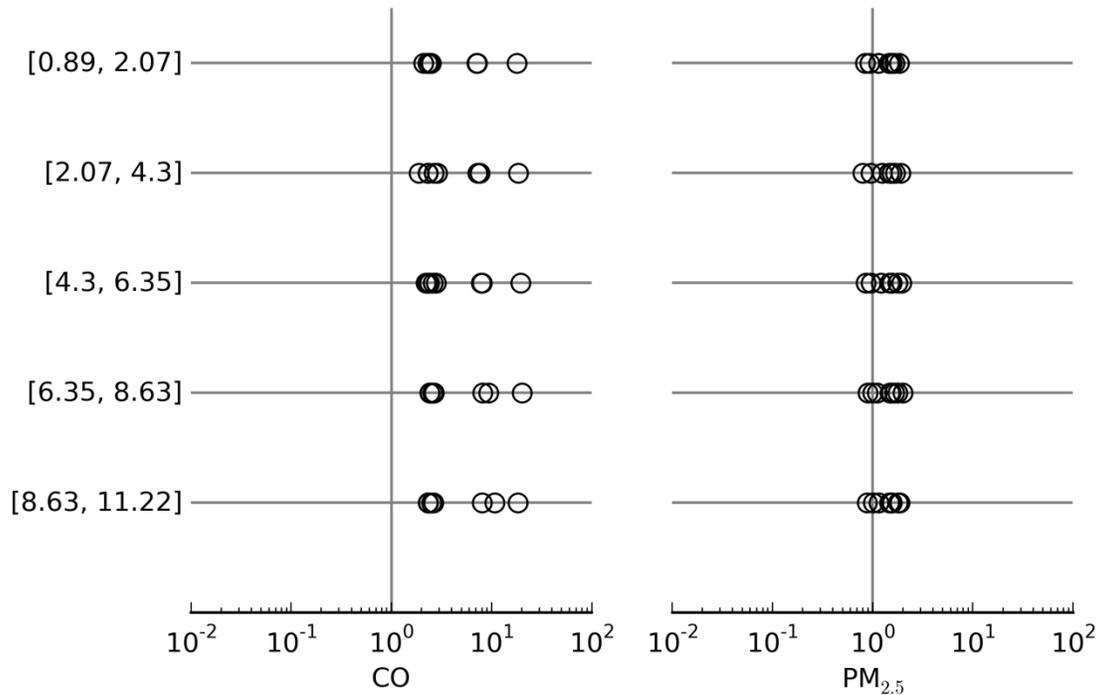


**Figure 3-2. Relative error for each segment by pollutant and range of values for $A^a$. Errors change little across the different levels of $A^a$.**

## Free-flow model

*Acceleration look-up table calibration*
To calibrate the free-flow model, we begin with $T^a$, which is a look-up table and bi-linear interpolation function. This parameter is the core of the free-flow model, and so it is a good place to start.

The lookup table (**Table 3-1**) consists of different acceleration rates by vehicle weight-to-power ratio (rows) and speed (columns). In the simulation, the acceleration of each vehicle is calculated by interpolating between the acceleration values in this table based on the vehicle's weight-to-power ratio and current speed. The values in the look-up table are critical in determining the simulated acceleration behavior.

24

To calibrate the parameter $T^u$ the values in the look-up table were varied from the default values, and the changed values were tested using a series of simulations, guided by a number of considerations, as follows:

First, the weight-to-power ratio of the probe vehicle was 27 lbs per hp, which falls between the first and second rows of Table . This meant that only the first and second rows would have an effect on the simulated probe vehicles. Therefore, only the first and second rows were varied, and the other rows were not changed.

Second, because the probe vehicle's weight-to-power ratio fell between rows, the simulation would calculate the acceleration by interpolating between rows. To negate the effect of interpolation and more directly control the calculated acceleration values, the first and second rows were always set to be the same as each other.

Third, each row in the look-up table has six values. It would have been difficult to calibrate all six of these values. For example, if we had wanted to test each value at four different levels, there would have been $4^6 = 4096$ combinations to test with several simulations each. Given the relative expense of running simulations, testing this number of combinations would have been unwieldy. To simplify the calibration process we sought to re-parameterize the model with fewer parameters, and yet still maintain a model form that could reasonably predict real-world behavior. The model was re-parameterized using the linearly-decreasing acceleration model because it has only two parameters

The linearly-decreasing acceleration model is given by

$$\dot{V} = max(\theta_1 - \frac{\theta_1}{\theta_2}s \ , 0.1) \qquad\qquad [v]$$

where $\dot{V}$ is the acceleration in fpsps, $s$ is the current speed (in miles per hour); $\theta_1$ is a parameter with units of fpsps, and $\theta_2$ is a parameter with units of mph. The parameter $\theta_1$ represents the acceleration when a vehicle is just starting from a stop, and is the maximum acceleration achieved. The parameter $\theta_2$ represents the target speed, or the speed at which acceleration becomes zero. Using these two parameters, the model predicts that acceleration starts out at $\theta_1$ as the vehicle starts from a stop, and then decreases linearly with speed until the acceleration reached zero when the target speed $\theta_2$ is achieved.

To calibrate the model, we tested $\theta_1$ and $\theta_2$ simultaneously over ranges of values. For each unique combination of values for $\theta_1$ and $\theta_2$ we calculated the six acceleration values for the first and second rows of the look-up table $T^u$. This calculation was performed by entering the speeds associated with each of the six columns of the lookup table into Equation v. The six calculated acceleration values were then entered into the look-up table before running the simulation.

For the calibration process we allowed $\theta_1$ to vary between 3.1 and 12.0; and $\theta_2$ to vary between 25 and 128. Each parameter was varied independently. We ran the simulation 300 times and the results were divided into 16 groups based on the values of $\theta_1$ and $\theta_2$ values that were used in the simulation.

The MLRE results show significantly more sensitivity to these free-flow model parameters than to the car-following parameters. For both pollutants, the best MLRE occurs when $\theta_1$ (starting acceleration) is between 8.6 and 12.0 fpsps, and $\theta_2$ (target speed) is between 25 and 41 mph (**Figure 3-3**).

It is not possible to compare these results directly to results for the default look-up table values, because the default values don't fall on a straight line and so can't be produced

by any combination of values for $\theta_1$ and $\theta_2$. However, we did estimate lines that approximate the default values using least-squares fitting. The least-squares fit to the default values in each of the first two rows yields parameter values of about 9.5 fpsps and 120 mph for the first row; and 8.2 fpsps and 110 mph for the second row. The calibrated range for $\theta_1$ (8.6-12.0) is near the approximated default values for $\theta_1$ (9.5 and 8.2), but the calibrated range for $\theta_2$ (25-41 mph) is much less than the default approximated values (120 and 110 mph).

This difference reflects a major change to the acceleration model resulting from the calibration process. Under the default parameters, acceleration decreases gradually from the starting acceleration until the vehicle is very near the target speed. Then the sub-model forces the acceleration to drop quickly to zero. Under the calibrated parameters, the acceleration decreases more quickly from the starting acceleration, and approaches zero smoothly. When the sub-model takes over, the acceleration is already near zero so the drop is not severe more accurately reflecting the driving behavior of the probe vehicle.

Before continuing with the calibration we set the $\theta_1$ and $\theta_2$ parameters to the approximate midpoints of their calibrated ranges, 10 fpsps and 33 mph. With these parameters the values in the first two rows of the lookup table are 10.0, 7.0, 3.9, 0.9, 0.1, and 0.1.

*Calibration of the Effect of Grade*
Because the errors showed significant sensitivity to the free-flow lookup table, the free-flow parameter *g*, was examined.

The default value for *g* is 30.5 fpsps. It is allowed to vary between 0 and 32.15. We ran 100 simulations and allowed the parameter to vary between 0 and 32.15. The simulation results were divided into 5 groups for an average of 20 simulations per group.

For CO, the smallest errors occurred when g was between 15 and 21.98. For $PM_{2.5}$, the smallest errors occurred when g was between 26.89 and 32.05. We compromise between the best calibration for CO and the best for PM2.5 by choosing the range (21.98, 26.89), which gives the second-best results for PM2.5, and near second-best results for CO. Within that range we set *g* to be 24 fpsps (approximate midpoint).

| Range for $\theta_1$ | Range for $\theta_2$ | MLRE | |
|---|---|---|---|
| | | CO | PM$_{2.5}$ |
| (3.1, 5.1) | (25, 41) | 0.459 | 0.268 |
| (3.1, 5.1) | (41, 51) | 0.448 | 0.250 |
| (3.1, 5.1) | (51, 70) | 0.403 | 0.205 |
| (3.1, 5.1) | (70, 128) | 0.453 | 0.198 |
| (5.1, 6.7) | (25, 41) | 0.312 | 0.176 |
| (5.1, 6.7) | (41, 51) | 0.339 | 0.141 |
| (5.1, 6.7) | (51, 70) | 0.395 | 0.114 |
| (5.1, 6.7) | (70, 128) | 0.410 | 0.132 |
| (6.7, 8.6) | (25, 41) | 0.288 | 0.111 |
| (6.7, 8.6) | (41, 51) | 0.309 | 0.075 |
| (6.7, 8.6) | (51, 70) | 0.342 | 0.111 |
| (6.7, 8.6) | (70, 128) | 0.488 | 0.143 |
| **(8.6, 12.0)** | **(25, 41)** | **0.196** | **0.071 (approx. linearly-decreasing model)** |
| (8.6, 12.0) | (41, 51) | 0.455 | 0.113 |
| (8.6, 12.0) | (51, 70) | 0.575 | 0.140 |
| *(8.6, 12.0)* | *(70, 128)* | *0.599* | *0.133 (approx. near-constant model)* |
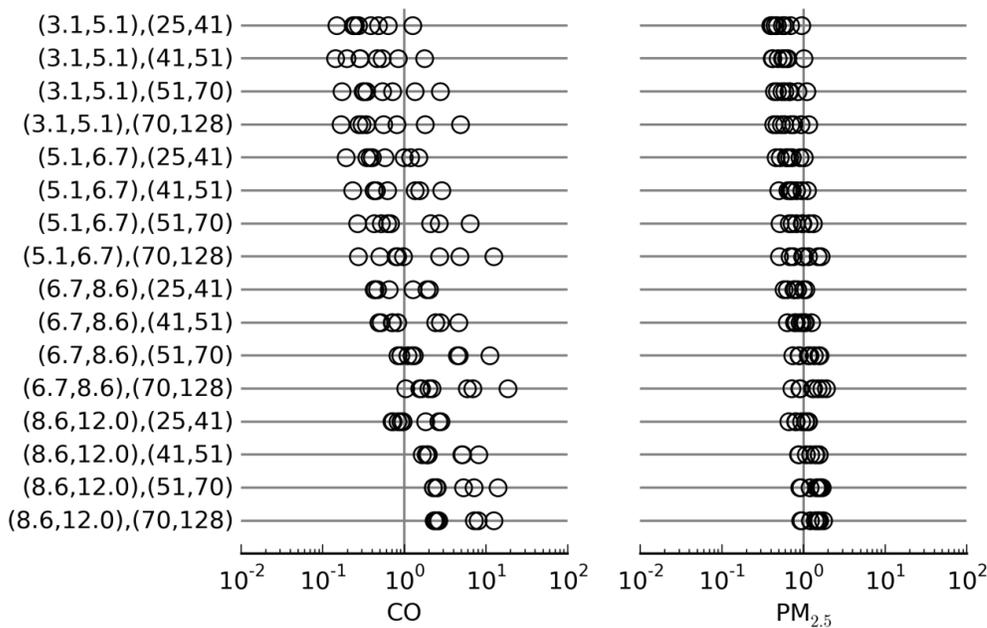


**Figure 3-3. MLRE by Pollutant and Ranges of Value of $\theta_1$ and $\theta_2$**

## 3.7 Model Validation

Using the calibrated parameters to calibrate the microsimulation model, we ran the simulation 30 times. The emissions rates were then calculated from the simulation data for

the seven validation segments. Then the MLRE was calculated for each segment. For comparison, we also ran the model 30 times with the default parameters, and calculated the MLRE. For all seven validation segments and both pollutants the calibrated model performed better than the default model (**Figure 3-4**).

| | Log Relative Error | | | |
|---|---|---|---|---|
| | CO | | $PM_{2.5}$ | |
| Segment | Default | Calibrated | Default | Calibrated |
| 3 | 0.902 | 0.286 | 0.067 | -0.037 |
| 4 | 0.963 | 0.282 | 0.051 | -0.050 |
| 6 | 1.252 | 0.579 | 0.283 | 0.108 |
| 8 | 0.377 | -0.079 | 0.076 | 0.001 |
| 10 | 0.564 | 0.067 | 0.161 | 0.055 |
| 14 | 0.289 | -0.183 | 0.142 | -0.039 |
| 15 | 0.405 | -0.014 | 0.156 | 0.033 |
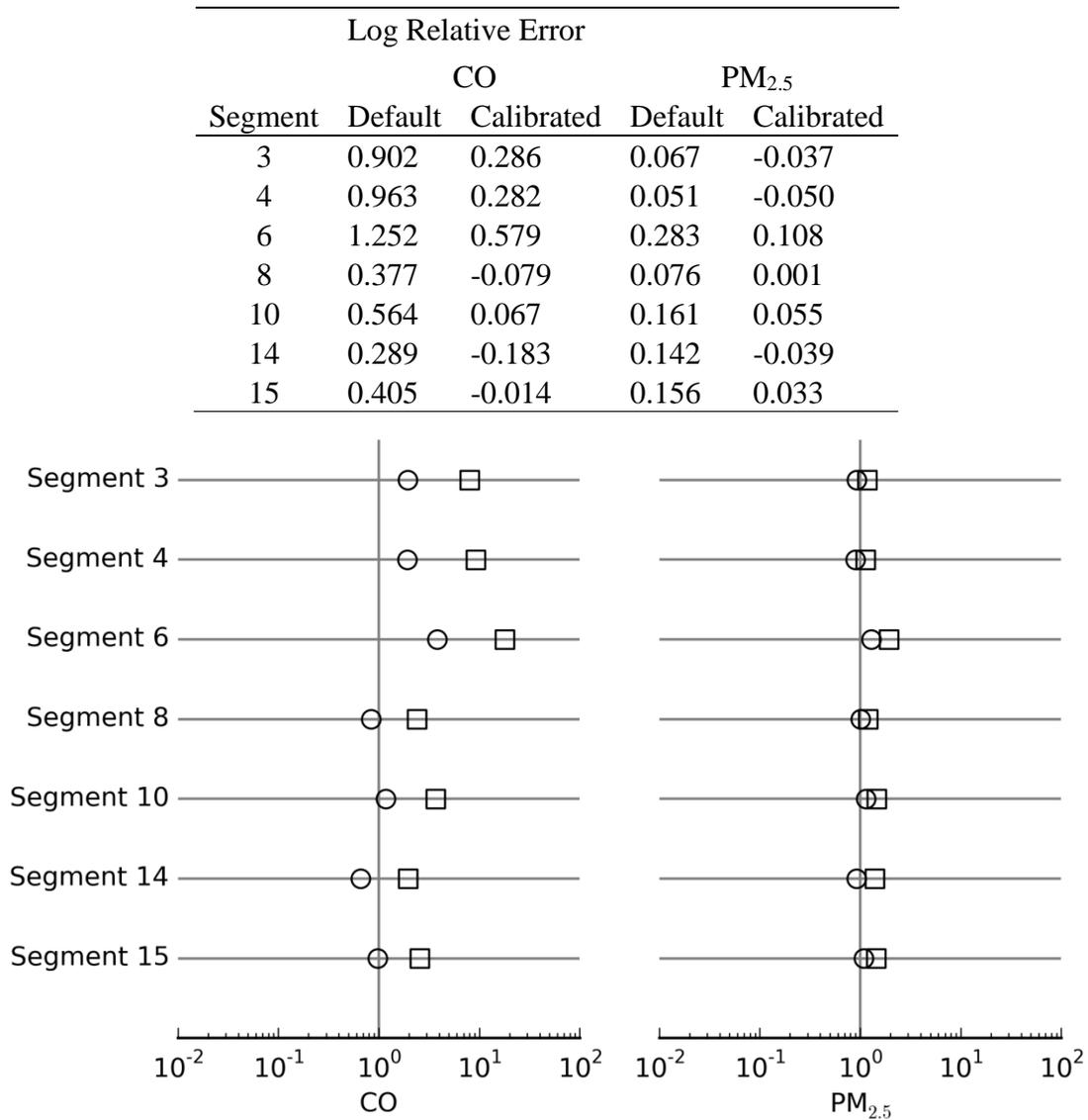


**Figure 3-4. Log Relative Error for Each Segment by Pollutant for the Default (squared) and Calibrated (circles) Parameters**

## 3.8 Comparison of the Default and Calibrated Models

We compare the default and calibrated models three ways:
**(1) Vehicle trajectories for vehicles starting from a stop**
The most important calibration adjustment to the model was adjusting the free-flow acceleration lookup table $T^a$. To understand the effect of this adjustment, we constructed a

simulation model with a single one-way roadway with a stop sign near it's midpoint. Vehicles entered the network from one end of the roadway, stopped at the stop sign, then continued on to exit the network. We ran the simulation once with the default parameters, and once with the calibrated parameters. We then isolated the part of each vehicle trajectory associated with accelerating from a stop to target speed. The speed/acceleration traces are plotted in **Figure 3-5**. The calibrated trajectories decrease in acceleration with respect to velocity more quickly than do the default trajectories. This has the effect that the calibrated vehicles achieve their target speed more gradually, and that accelerations are less and less extreme as speed increases compared to the default.

## (2) VSP distribution

To compare the VSP distributions of the default and calibrated parameters, we ran the simulation 30 times using the default parameters, and 30 times using the calibrated parameters. We then calculated the VSP distribution across all 30 simulations and 15 segments for each of the 2 parameter sets. The distributions are compared in **Figure 3-6**. In the positive VSP range, calibrated parameters produced less extreme VSP values than did the default parameters. The calibrated VSP range was similar to the TOTEMS real-world values.

## (3) Operating mode distribution

We compared the operating mode distributions of the default and calibrated parameters using the same sets of 30 simulations. The operating modes were 'weighted' by multiplying each distribution proportion by the associated MOVES emissions rate. This has the effect of giving more importance to those operating modes that have higher emissions rates and thus have more effect on the total emissions estimate.

The weighted operating mode distributions are presented in **Figure 3-7**. For both CO and $PM_{2.5}$, the largest differences are for operating mode 30, where the default parameters lead to over-production of project-level emissions. Operating mode 30 is the highest VSP bin available for speeds between 25 and 50 miles per hour. For both CO and PM2.5, operating mode 30 has the highest emission rate of any operating mode, which means that even small errors in distribution for this operating mode can produce large errors in link emissions estimates. This fact is illustrated by the large difference between the default and calibrated weighted operating mode distributions (**Figure 3-7**). The default parameters over-estimate the distribution for this bin because they predict relatively extreme accelerations for speeds between 25 and 50 mph. The calibrated parameters generate more moderate accelerations.
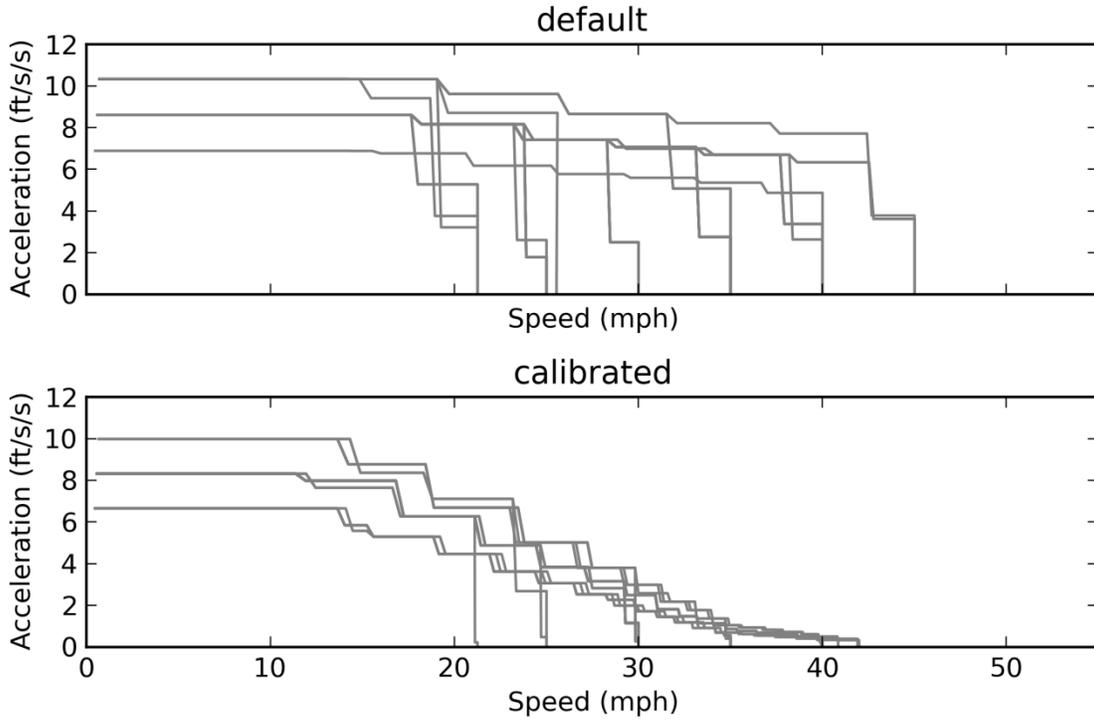
**Figure 3-3. Vehicle speed-acceleration traces from a contrived simulation for the default parameters (top) and calibrated parameters (bottom). Acceleration decreases more rapidly for the calibrated model than for the default model as speed approaches the target speed.**
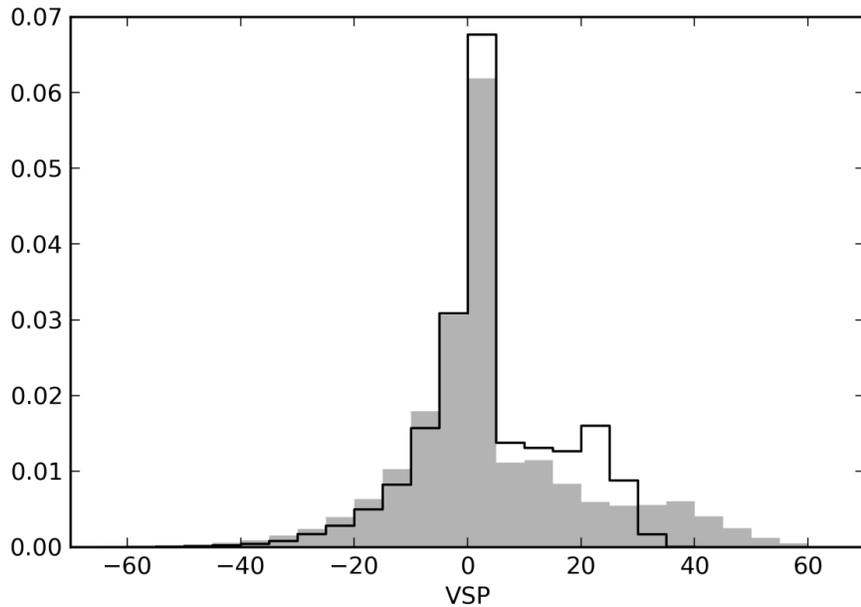


**Figure 3-4. VSP distribution for all 15 segments for the calibrated parameters (black line) and the default parameters (gray fill). The calibrated distribution has less extreme values in the positive range.**
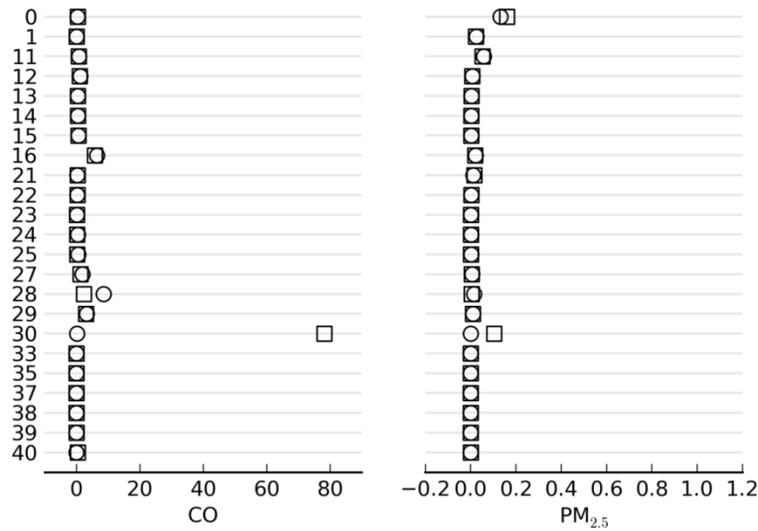
**Figure 3-5. Product of operating mode distribution and emissions rate for each operating mode, for the calibrated parameters (circles) and the default parameters (squares). Operating mode 30 contributed the most to overall emissions estimate errors.**

## 3.9 Discussion and Conclusion

This research demonstrates that traffic microsimulation models can be calibrated to more closely track the operating mode distributions of real world traffic. This is a critical finding if microsimulation models are to be used for estimating mobile emissions, particularly for project-level air quality analysis.

The key finding from this research is that default model parameters within the microsimulation model software (TransModeler) tested in this research are typically not well calibrated for the needs of an emissions analysis. This finding reinforces similar findings from previous research. Notably, while the default parameters within the car-following model showed virtually no impact on the resulting emissions, the default parameters within the free-flow model were critical in affecting emissions results. Specifically, the rate of acceleration as the target operating speed is being approach is a key parameter that must be adjusted by the model user to more accurately replicate real world motorist behavior. The techniques employed here suggest that vehicle trajectory plots of a simple stop-and-go simulation for the vehicle types (power-to-weight, acceleration limits) of interest in a microsimulation/emissions study can be used to identify appropriate free-flow model parameters.

The research utilized one of the commercial software microsimulation packages, TransModeler. Future research should investigate other microsimulation tools to identify comparable parameters in the free-flow model that can be adjusted to better replicate real world driver behavior.

This research suggests that the default free-flow model parameters will result in over-estimating acceleration intensity and, hence, resulting project-level emissions.

Reducing the intensity of acceleration as the target operating speed is approached provides a much more accurate estimate of driver behavior and of the resulting emissions.

## 3.10 Acknowledgment

# 4.0 References Cited

1.  "EPA Issues Transportation Conformity Guidance for Quantitative Hot-spot Analyses in PM $_{2.5}$ and PM$_{10}$ Nonattainment and Maintenance Areas" EPA-420-F-10-052. December 2010.
2.  Chamberlin, Robert and Ben Swanson and Eric Talbot. "Utilizing MOVES for Estimating Traffic Operational Emissions Impacts" presentation to the TRB ADC20 Committee at the Transportation Planning, Land Use, and Air Quality Conference. May 2011.
3.  Byun, John. "Integrating Second-by-Second Traffic Movement Data Generated from Traffic Simulation Models onto MOVES Project Level Analyses." At: http://www.epa.gov/otaq/models/moves/conference2011/traffic-simulation-moves-2011.pdf
4.  EPA, MOVES Operating Mode Distribution Generator. EPA-420-B-12-037. May 2012.
5.  Chamberlin, Robert, Ben Swanson, Eric Talbot, Subramanian Sharma, and Peter Crouch. Toward Best Practices for Conducting a MOVES Project-Level Analysis. Paper 12-036. Transportation Research Board Annual Meeting. 2012.
6.  Chamberlin, Robert, "Utilizing the MOVES Link Drive Schedule for Analyzing a Project-Level Emissions Impact". Presentation to the Transportation Research Board Committee on Transportation and Air Quality Session on Integrating the EPA MOVES Model with Transportation Microsimulation Models. January 23, 2011.
7.  Hallmark, Shauna, and Randall Guensler. "Comparison of Speed-Acceleration Profiles from Field Data with NETSIM Output for Modal Air Quality Anlaysis of Signalized Intersections. TRR 1664 Paper No. 99-1288.
8.  Viti, Francesco, Serge P. Hoogendoorn, Henk J. van Zuylen, Isabel R. Wilmink, and Bart van Arem. "Speed and Acceleration Distributions at a Traffic Signal Analyzed from Microscopic Real and Simulated Data." Proceedings of the 11$^{th}$ International IEEE Conference on ITS. 2008.
9.  Song, Guohua, Lei Yu, and Yanhong Zhang. Applicability of Traffic Microsimulation Models in Vehicle Emissions Estimations: A Case Study of VISSIM. TRB Annual Meeting 2012.Chamberlin, Robert and Ben Swanson, Eric Talbot, Jeff Dumont, and Steven Pesci. "Analysis of MOVES and CMEM for Evaluating the Emissions Impact of an Intersection Control Change". TRB 2011 Annual Conference Paper 11-0673.
10. Papson, Andrew, Seth Hartley and Kai-Ling Kuo. Analysis of Emissions at Congested and Uncongested Intersections Using MOVES 2010. TRB 12-0684. TRB 2012 Annual Meeting.
11. E. H. Pechan & Associates. Advances in Project Level Analysis. Final Report Prepared for FHWA under DTFH61-10-C-0006. November 4, 2010.
12. Holmén, Britt A., Mitchell Robinson, Karen Sentoff, Paul Montane, Kevin Hathaway (2009). Proof-of-Concept Report: The On-Board Tailpipe Emissions Measurement System (TOTEMS), Report to the UVM Transportation Research Center, June 3, 2009. TRC Report # 10-015.
13. Robinson, M.K., Sentoff, K., B. A. Holmén (2010) Particle Number and Size Distribution Emissions During Light-Duty Vehicle Cold Start Using the TOTEMS On-Board Measurement System. Transportation Research Board: Washington D.C. 2010, Paper #10-3038.
14. Holmén, B.A., K.M. Sentoff, M.K. Robinson, and P. Montane (2010) The University of Vermont TOTEMS Instrumentation Package for Real-World, On-Board Tailpipe Emissions Monitoring of Conventional and Hybrid Light-Duty Vehicles. Transportation Research Board: Washington D.C. 2010, Paper # 10-3023.
15. http://www.epa.gov/otaq/models/moves/
16. Hallmark, Shauna, and Randall Guensler. "Comparison of Speed-Acceleration Profiles from Field Data with NETSIM Output for Modal Air Quality Anlaysis of Signalized Intersections. TRR 1664 Paper No. 99-1288.

17. E. H. Pechan & Associates. Advances in Project Level Analysis. Final Report Prepared for FHWA under DTFH61-10-C-0006. November 4, 2010.

18. Chamberlin, Robert, "Utilizing the MOVES Link Drive Schedule for Analyzing a Project-Level Emissions Impact". Presentation to the Transportation Research Board Committee on Transportation and Air Quality Session on Integrating the EPA MOVES Model with Transportation Microsimulation Models. January 23, 2011.

19. Chamberlin, Robert and Ben Swanson, Eric Talbot, Jeff Dumont, and Steven Pesci. "Analysis of MOVES and CMEM for Evaluating the Emissions Impact of an Intersection Control Change". TRB Annual Meeting 2011.

20. Chamberlin, Robert, Ben Swanson, Eric Talbot, Subramanian Sharma, and Peter Crouch. Toward Best Practices for Conducting a MOVES Project-Level Analysis. Paper 12-036. Transportation Research Board Annual Meeting 2012.

21. Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software. http://www.ops.fhwa.dot.gov/trafficanalysistools/tat_vol3/vol3_guidelines.pdf

22. Song, Guohua, Lei Yu, and Yanhong Zhang. Applicability of Traffic Microsimulation Models in Vehicle Emissions Estimations: A Case Study of VISSIM. TRB Annual Meeting 2012.

23. Viti, Francesco, Serge P. Hoogendoorn, Henk J. van Zuylen, Isabel R. Wilmink, and Bart van Arem. "Speed and Acceleration Distributions at a Traffic Signal Analyzed from Microscopic Real and Simulated Data." Proceedings of the 11th International IEEE Conference on ITS. 2008.

24. Motor Vehicle Emission Simulator (MOVES) User Guide for MOVES2010b. http://www.epa.gov/otaq/models/moves/documents/420b12001b.pdf

25. Byun, John. "Integrating Second-by-Second Traffic Movement Data Generated from Traffic Simulation Models onto MOVES Project Level Analyses." At: http://www.epa.gov/otaq/models/moves/conference2011/traffic-simulation-moves-2011.pdf

26. Transportation Conformity Guidance for Quantitative Hot-spot Analyses in PM2.5 and PM10 Nonattainment and Maintenance Areas. December 2010.

27. TransModeler Traffic Microsimulation Software. Caliper Corporation. Newton, MA. http://www.caliper.com/transmodeler/

28. Holmén, Britt A., Mitchell Robinson, Karen Sentoff, Paul Montane, Kevin Hathaway (2009). Proof-of-Concept Report: The On-Board Tailpipe Emissions Measurement System (TOTEMS), Report to the UVM Transportation Research Center, June 3, 2009. TRC Report # 10-015.

29. Robinson, M.K., Sentoff, K., B. A. Holmén (2010) Particle Number and Size Distribution Emissions During Light-Duty Vehicle Cold Start Using the TOTEMS On-Board Measurement System. Transportation Research Board: Washington D.C. 2010, Paper #10-3038.

30. Holmén, B.A., K.M. Sentoff, M.K. Robinson, and P. Montane (2010) The University of Vermont TOTEMS Instrumentation Package for Real-World, On-Board Tailpipe Emissions Monitoring of Conventional and Hybrid Light-Duty Vehicles. Transportation Research Board: Washington D.C. 2010, Paper # 10-3023.