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Publication Date

2005

Designing On-Road Vehicle Test Programs for Effective Vehicle Emission Model Development

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TRB Paper No. 05-2770
Submission date: July 30th, 2004; revised: November 16th, 2004; finalized: March 15, 2005
Revised for Transportation Research Record: 4/1/2004

Word count, including abstract, references, figures and tables: 6645
Abstract word count: 203

ABSTRACT

Mobile source emission models for years have depended on laboratory-based dynamometer data. In recent years however, portable emission measurement systems (PEMS) have become commercially available and in widespread use, making on-road real-world measurements possible. As a result, the newest mobile source emission models (e.g., U.S. EPA's Mobile Vehicle Emission Simulator) are becoming increasingly dependent on PEMS data. Although on-road measurements are made under more realistic conditions compared to laboratory-based dynamometer test cycles, they also introduce additional influencing variables that must be carefully measured in order to properly develop emission models. Further, test programs that simply measure in-use driving patterns of randomly selected vehicles will result in models that can effectively predict current-year emission inventories for typical driving conditions. However, when predicting more aggressive transportation operations than current typical operation, (e.g., higher speeds, accelerations, etc.), the model predictions will be less certain. In this paper, various issues associated with on-road emission measurements and modeling are presented. Further, we examine an example on-road emissions dataset and the reduction in estimation error through the addition of a short aggressive driving test to the in-use data. Based on these results, recommendations are made on how to improve the on-road test programs for developing more robust emission models.

Keywords: vehicle activity patterns, portable emission measurement systems

1. INTRODUCTION

Over the last several decades, there has been a significant amount of activity in developing increasingly accurate mobile source emission models. Predicting emissions from motor vehicles is an integral part of many programs aimed at improving air quality in non-attainment regions of the U.S. The Clean Air Act Amendments (CAAA) of 1990 and subsequent transportation funding bills place great emphasis on modeling to provide accurate accounting of progress toward meeting air quality goals and deadlines, that if not met could lead to highway funds being withheld. Congestion mitigation and transportation management strategies will only be possible if it can be shown that their implementation will not further degrade the air quality in specific urban areas.

The primary mobile source emission models developed for regulatory purposes have been the U.S. Environmental Protection Agency's (U.S. EPA) MOBILE model and California Air Resources Board's (CARB) EMFAC model. Both of these models have incrementally improved over the years with updated versions. These models were initially developed based on specific certification driving cycles that were assumed to represent average or typical driving. Base emission rates were developed primarily from laboratory dynamometer tests running these certification cycles. In the mid-1990s, it was recognized that these certification cycles were not very representative of modern traffic driving patterns, leading to the development of improved driving cycles such as CARB's Unified Cycle *(1)* and U.S. EPA's SFTP (supplemental federal test procedure, see *(2)*).

Further, the traditional models of MOBILE and EMFAC were intended to predict emission inventories for large regional areas and are not very well suited for evaluating traffic operations that are more "microscopic" in nature, such as ramp metering, signal coordination, and many transportation control measures. Subsequently, the U.S. EPA recognized the need for a new emissions modeling framework that is capable of predicting emissions across various scales. As a result, the U.S. EPA is currently developing MOVES (Motor Vehicle Emission Simulator) which is intended to replace MOBILE and their NONROAD model *(3, 4)*. MOVES will also have expanded capability, modeling additional emissions sources such as from aircraft, commercial marine, and locomotive, as well as addressing greenhouse gases. One of the major differences between the previous MOBILE series of models and MOVES is that MOVES will be based primarily on real-world, in-use vehicle emissions, as opposed to laboratory dynamometer-based data.

This shift from laboratory-based data to real-world in-use data coincides with recent improvements in on-board emission measurement technology. While available for several years, the instrumentation has grown in use and sophistication within the last few years. There are now several commercially available on-board emission measurement systems as well as several research programs that continue to improve the on-board measurement technology (e.g., see *(5, 6, 7, 8, 9)*). The advantage of on-board equipment is that you can now measure real-world emissions as the vehicles are driven on typical roadways under a variety of traffic conditions. These on-board emission measurement systems have also become quite portable, requiring just a few minutes to install in the target vehicles *(10)*. Further, the accuracy and precision of some PEMS are quite high: capable of measuring LEV, ULEV, and SULEV certified vehicles.

Several on-road data collection programs have already begun and several more are planned in the near future. These on-road programs provide much more realistic data compared to strictly laboratory testing. However, it is important to design the data collection program carefully so that the resulting data are maximally useful for emission model development. For example, it is crucial to recruit and instrument a statistically-sound sample of vehicles that a representative of the overall fleet. Further, it is important to collect emissions data from a wide-variety of driving conditions. In many cases drivers in real-world situations will not necessarily cover the entire performance "envelope" of the vehicles. If a model is to predict emissions under a variety of driving conditions (that is influenced by different levels of traffic conditions), it is important to collect data across a wide range of vehicle operation. A statistical examination of the influence of on-road factors on the variability and uncertainty of NOx from motor vehicles found substantial variability due to vehicle to vehicle differences as well as to driving cycles *(11)*. In addition, an uncertainty analysis of MOBILE5 including temperature correction factors has been reported *(12)*. More recently, NC State evaluated variability and uncertainty in emissions from mobile sources in their final report to the EPA as part of the MOVES data analysis shootout *(13)*.

In this paper, we briefly outline key issues of on-road emissions data collection. This is followed by an analysis of a dataset of an initial on-road data collection program and show how data from limited vehicle operation can lead to high degrees of uncertainty in resulting emission models that need to predict emissions across a wide variety of conditions. Suggestions are made on how on-road data collection programs can be enhanced through some simple steps in order to ensure robust models.

2. ON-ROAD EMISSIONS DATA COLLECTION

Portable emissions measurement systems (PEMS) are very beneficial in obtaining data that are truly representative of real-world emissions. Laboratory dynamometer-based testing has been carried out for years and there have always been questions on how well the driving cycles used represent real-world conditions. Further, in the past a vehicle's emission control systems have been designed to meet tailpipe emission certification levels, but they may not operate in the same manner during "off-cycle" events (e.g., hard accelerations, etc.). When performed correctly, on-board emissions testing will provide a wealth of information on real-world driving conditions.

PEMS units vary somewhat from manufacturer to manufacturer, but in general rugged models are available for use in on-road light duty applications as well as in off-road heavy duty applications with higher dust and vibration. They are designed to function under a wide range of ambient conditions, typically from near zero degrees Celsius up to 40 degrees Celsius. One constraint imposed by the current level of equipment is a relatively long warm-up times of up to an hour for the instrumentation. This results in the loss of some initial data or the use of careful protocols for data collection. Post processing of the data varies from instrument to instrument, but in general involves time alignment and conversion from concentration to mass measurement.

However, it is important to understand that on-road emissions data collection cannot completely replace laboratory-based programs. On-road data collection programs will result in real-world emissions data that are influenced by numerous factors including varied vehicle characteristics, traffic, driving behavior, road grade, and even meteorological conditions. All of these factors (and several more) affect tailpipe emissions and it is very difficult to control these factors individually. For example, if it was desired to carry out testing under specific temperatures, this is difficult to design in the real world. In the laboratory, it is somewhat easier to control specific factors individually so that the "confounding factors" issue is minimized.

Further, on-board emission measurement equipment currently measure specific tailpipe emission species (e.g., CO, HC, NOx, CO_2, and particulate matter). Other pollutants (e.g., air toxics) are of equal or greater concern and currently can only be measured with laboratory-based equipment. It is also important to point out that the on-board equipment can only measure tailpipe emissions. With the improvement of emission control technology, evaporative emissions are becoming an increasing larger fraction of total vehicle emissions which still must be carefully managed. Evaporative emissions must be measured under closely controlled laboratory conditions.

As stated previously, it is difficult to control emissions-influencing factors during real-world testing. Even though they can be closely controlled, the different factors that influence vehicle emissions should at a minimum be measured along with the emissions data themselves. These data can then be used in the data analysis phase in identifying potential influencing factors. When designing an on-road emissions data collection program, there are several elements that need to be considered *(14)*:

> ***Vehicle Recruitment*—**it is crucial to recruit a wide variety of vehicles when carrying out data collection. In many cases, stratified random sampling techniques can be used based on having a priori knowledge of their potential emissions contribution. Various selection factors will include vehicle make, model, engine type and size, emission certification level, weight, and vehicle mileage. If possible, it is important to get a proper sampling of high emitting vehicles.
>
> ***Study Area and Route Selection*—**for a given study area, it will be desired to include a variety of location-specific factors including different roadway facility types (e.g., highway, arterial, residential roads), specific roadway facility elements (e.g., High Occupancy Vehicle (HOV) lanes, different intersection types, toll booths, etc.), different levels of traffic congestion, and influence of road grade.
>
> ***Temporal Issues*—**in many locations, the time of year, time of week, and time of day will play a role in vehicle emissions. For example, summertime emissions may be very different from colder wintertime emissions. Weekend travel will in many cases be different from weekday travel. Driving at peak traffic conditions compared to off-peak conditions will also have a significant influence.
>
> ***Vehicle Operation*—**how a vehicle is operated will also play an important role in an on-road emissions study. If the resulting model will attempt to predict for a wide range of driving conditions, then the dataset should cover a wide range of conditions. If possible, a wide range of driving behavior (e.g., mild to aggressive) should be included. It may also be necessary to have a short amount of “calibration” testing be performed, as outlined in the following section.

For the remainder of this paper, we focus on the importance of obtaining a wide variety of vehicle activity when testing emissions. An initial on-road emissions dataset is examined in detail to show how lack of activity data at high power levels may lead to a large amount of model uncertainty.

3. U.S. EPA'S "SHOOTOUT" DATASET ANALYSIS

During the early development of MOVES, the U.S. EPA devised an "on-board emissions analysis shootout" program to evaluate potential methods for using on-board emissions data to generate emission rates *(15)*. As part of this program, an on-board data collection effort was performed. On-board emission data (approximately 100,000 seconds) were gathered on 17 light-duty vehicles in the summer of 2001 in the Ann Arbor, Michigan area. Further, 15 heavy-duty diesel transit buses were also instrumented in the Fall 2001. All the light-duty vehicles in the sample were certified to federal Tier I tailpipe standards, with a model year range of 1996 through 2000, and had either 4 or 6 cylinder engines. The transit buses had a model year range of 1995 through 1997 and had similar mileage accumulation. Each vehicle was instrumented for a period of 1-3 days, during which period the owner was given no special instructions on how to operate the vehicle to ensure representative driving and operation patterns *(15)*.

3.1. Vehicle Activity Measures

The light-duty vehicle operation data have been analyzed in detail. To illustrate the variety of vehicle activity, Figure 1 shows example acceleration-velocity contour histograms of the driving data. In these diagrams, it is possible to see both the breadth of speed and acceleration. For Figure 1a, the standard FTP driving cycle is represented. The FTP is well known for being a very mild driving cycle, first developed in 1974 *(16)*. Figure 1b shows the histogram for vehicle 17 of the shootout dataset as an example of mild-activity conditions. This particular vehicle never went faster than 47 mph during the entire time it was instrumented in the study. Figure 1c and 1d show similar histograms for medium- and aggressive-activity patterns. Vehicle #13 has a significant amount of high-speed operation extending over 80 mph, while vehicle #14 has a mixture of low-, mid-, and high-speed driving. Figure 1e show the histogram for a fairly aggressive driving cycle, specifically the MEC01 which was developed for obtaining modal emission events as part of NCHRP Project 25-11 *(17)*. In addition to focusing on specific modes of operation such as steady-state cruise, acceleration, deceleration, etc., the MEC01 cycle pushes the vehicle to its maximum performance limits with wide-open throttles and high-speed driving.

Another method of examining vehicle activity and its influence on emissions is to calculate Vehicle Specific Power (VSP). VSP is a convenient single measure (rather than a dual parameter histogram such as velocity and acceleration) that can be used directly to predict emissions. The VSP approach to emissions characterization was developed by several researchers (an example being Jimenez-Palacios *(18)*) and further developed as part of the MOVES model. VSP is a measure of the road load on a vehicle; it is defined as the power per unit mass to overcome road grade, rolling & aerodynamic resistance, and inertial acceleration:

$$VSP = v * (a*(1+\gamma) + g*grade + g*C_R) + 2\rho*C_D*A*v^3/m$$

where:

v: is vehicle speed (assuming no headwind) in m/s
a: is vehicle acceleration in m/s^2
γ: is mass factor accounting for the rotational masses (~0.1)
g: is acceleration due to gravity
grade: is road grade
C_R: is rolling resistance (~0.0135)

ρ: is air density (1.2)
C_D: is aerodynamic drag coefficient
A: is the frontal area
m: is vehicle mass in metric tonnes.

Using typical values of coefficients, in SI units the equation becomes ($C_DA/m \sim 0.0005$):

$$\text{VSP (kW/metric Ton)} = v * (1.1*a + 9.81*\text{grade}(\%) + 0.132) + 0.001208*v^3$$

If we examine the same example vehicle activity sets described above, we can plot histograms of VSP values as shown in Figure 2. Again, the FTP is seen to be fairly mild and the MEC01 cycle is very aggressive with a maximum value near 400 kW/metric ton. Vehicle #14 actually had higher VSP values than the MEC01, extending beyond 400.

3.2. VSP-Based Emission Measures

Several mobile source emission models (including MOVES) use VSP as the primary parameter for predicting emissions. From the initial work in MOVES, specific "VSP bins" were created for predicting emissions in each bin. These bin definitions are shown in Table 1. Using these bin definitions, we have taken the second-by-second driving measurements for the entire light-duty fleet of the shootout dataset and created VSP-bin histograms using CMEM modeled emissions, along with error bars that represent 95% confidence bands, shown in Figure 3. The actual vehicle emissions were replaced with CMEM modeled emissions for this analysis to remove vehicle variability from the examination of reductions in variability through additional testing. In addition, the use of modeled data allowed for comparison of additional test data that was not collected as part of the MOVES program without having to try and compensate for differences in test programs. The addition of a hard driving test cycle was then simulated for each vehicle by using CMEM to model the MEC driving cycle.

It can be seen in Figure 3 that the largest error bars are at the higher emission bins. This is due to the general a lack of emissions data for the higher power events. Based on these data alone, an emission model would have a higher degree of uncertainty for all driving cycles where a large amount of vehicle activity fell into these higher power bins. For example, if a transportation improvement project allowed for previously congested traffic to travel at higher speeds and accelerations, then the model would not be able to predict accurately since the model was previously "calibrated" primarily with lower-power emissions.

To avoid this potential pitfall, it is recommended that a small amount of prescribed high-powered driving take place as part of the on-road emission study. A small number of prescribed high-power events could be made part of the initial calibration step when the instrumentation is first placed in the vehicle.

The error bars in Figure 3 are based on a total of 71,892 seconds of driving time collected on the MOVES data analysis shootout vehicles using modeled emissions results. This represents a minimum variability situation because it removes the vehicle variability. The next step was to estimate the reduction in variability within VSP bins that could be achieved through the addition of a hard driving pre-or post data collection driving schedule. Say, for example that approximately 15 minutes of high power driving is added to each vehicles testing. This is the equivalent of adding something like the first 900-second MEC01 cycle to the existing driving data. Without actually conducting the additional data collection, there are three main methods of illustrating this concept. The first would be to use additional data from other vehicles. The second would be to re-sample the data already collected on the vehicles in this paper, and the third is to use a second-by-second model to replicate the additional test data. Using additional data from other vehicles would inject vehicle-to vehicle variability into the problem, when we are trying to estimate the effect of additional data collection within vehicles. Re-sampling on the other hand was limited to replication of the limited number of seconds of data available in the high power levels and would under-represent the variability within the power bins because of the limits on data that have been previously discussed. CMEM modeling of the additional data was chosen as a compromise because it has lower variability than including data from other vehicles, but it does allow for filling out more points within the VSP bins than the actual vehicle data.

To show the effects of the additional data collection, we have taken the MEC01 cycle, created emission values using the CMEM model calibrated for the proper vehicle category *(17)*, and added the emission values to the overall dataset. We then plotted the same VSP-binned emissions data to examine the effect on the error, as shown in Figure 4. Table 2 presents the percentage reduction in Standard Error by VSP bin for CO_2, CO, HC, and NO_x.

3.3. Cycle-Based Emission Measures

Variability of the emissions estimates is dependent upon the VSP bin. Data augmentation has a greater effect on lowering the variability of the estimates for higher power VSP bins, resulting in greater reductions in variability for harder driving cycles. Estimates of CO were generated for the FTP and MEC cycles using the bin data from the previous section, with upper and lower confidence limits calculated for both the on-road data and the augmented on-road data. Upper and lower estimates of the cycle total CO emissions were calculated by estimating the cycle totals using the upper limits of each VSP bin and the lower limits for each VSP bin. Data augmentation had a greater effect on the size of the confidence limits for the MEC cycle (Table 3).

4. RECOMMENDED TEST PROCEDURE

To enhance the utility of future on-road data sets, we propose the inclusion of an informal driving cycle which includes high power and high speed events. Having pre-specified second-by-second driving traces for on-road data is impractical, however a series of specific driving events could easily be added to the installation procedure prior to returning the vehicle to the owner for in-use data collection or conducted prior to removal of the PEMS unit from the vehicle. The additional driving would most likely be conducted by the equipment installation crew. The series of driving events should be conducted in a safe location and on a minimal grade.

The informal driving cycle consists of the following driving events:

- Accelerations – A series of accelerations up to a freeway speed of 65 mph, at 50% throttle, 75% throttle, 90% throttle, and wide open throttle.
- Extended decelerations – Three decelerations from a freeway speed of 65 mph to a complete stop.

- AC operation – Steady-state cruises having duration of 90 seconds and speeds of 25, 45, 55, and 70 mph with and without AC engaged.

Individual drivers do not necessarily cover the full range of vehicle operation needed for optimal model building in typical day-to-day use. This cycle, used in conjunction with a standard installation, would shorten the time necessary for instrumentation by removing the necessity of collecting sufficient data to capture the lower probability events at the very high and very low power levels. Addition of a simple series of driving events to the installation procedure can ensure data collection over the full range of vehicle performance. The addition of the augmented driving can greatly reduce the data collection time on individual vehicles for modeling purposes.

5. SUMMARY AND CONCLUSIONS

Collection of emissions data from typical in-use vehicles provides an unbiased data source for modeling of on-road emissions. However, many issues need to be considered when setting up a on-road emissions test program, outlined in Section 2. Among other issues, we have shown that simply instrumenting vehicles and collecting in-use driving data will typically have higher variability in the estimates of emissions for higher power VSP bins due to the reduced number of seconds of data usually available under high power conditions.

To avoid this potential pitfall, it is recommended that a small amount of prescribed high-powered driving take place as part of the on-road emission study. A small number of prescribed high-power events could be made part of the initial calibration step when the instrumentation is first placed in the vehicle. This is due to the fact that drivers in real-world situations do not always drive their vehicles under conditions that are represented by standard modal modeling driving cycles, such as hard accelerations and decelerations. By including a short driving procedure that could be performed immediately after installation or prior to removal of PEMS units in testing conditions, data could be collected that properly represent high-load events that are not currently captured by real-world driving of many motorists. The additional cost of collecting this data is low in comparison to the large benefits resulting from reductions in variability in the high-power bin emissions estimates.

The augmentation of the on-road data with the high-power augmentation data led to greater reductions in the size of the confidence intervals for the MEC cycle estimates than for the FTP cycle estimates. In general the use of a pre-specified driving schedule when collecting on-road data will produce greater benefits for reduction of model error on harder driving patterns than on milder driving.

An alternative to the in-use testing with the added pre-specified driving would be to just do the pre-specified driving on in-use vehicles without the extended in-use driving by the owner. This would produce data sets suitable for modal modeling, but would limit their use for inventory development. However, it would enable the rapid collection of data on a large numbers of in-use vehicles.

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TABLE AND FIGURE CAPTIONS

Figure 1: Acceleration-velocity contour histograms of a) FTP driving cycle; b, c, d) example vehicle activity patterns for a mild-, medium-, and aggressive-activity vehicles respectively; and e) the MEC01 driving cycle.

Figure 2: Vehicle Specific Power histograms of a) FTP driving cycle; b, c, d) example vehicle activity patterns for a mild-, medium-, and aggressive-activity vehicles respectively; and e) the MEC01 driving cycle. Maximum values are shown as a single line.

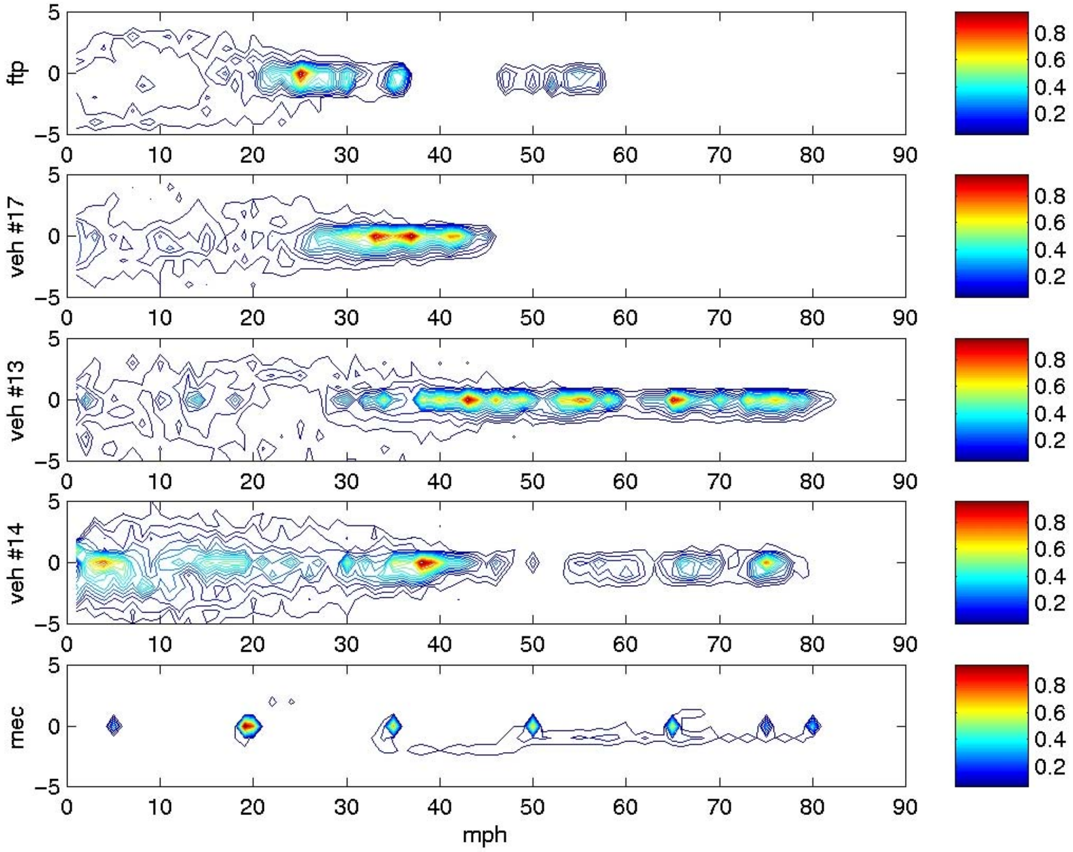
Figure 3: Light-duty emissions as a function of VSP bins defined Table 1. Error bars indicate 95% confidence interval. a) CO_2, b) CO, c) HC, d) NOx

Figure 4: Light-duty emissions (real-world + MEC01 data) as a function of VSP bins defined Table 1. Error bars indicate 95% confidence interval. a) CO_2, b) CO, c) HC, d) NOx

Table 1: Vehicle Specific Power bins used in preliminary MOVES model *(4)*.

Table 2: Percent reduction in standard error (S.E.) by VSP bin after inclusion of MEC data.

Table 3: Total cycle CO emissions estimate range (%) by cycle and data.



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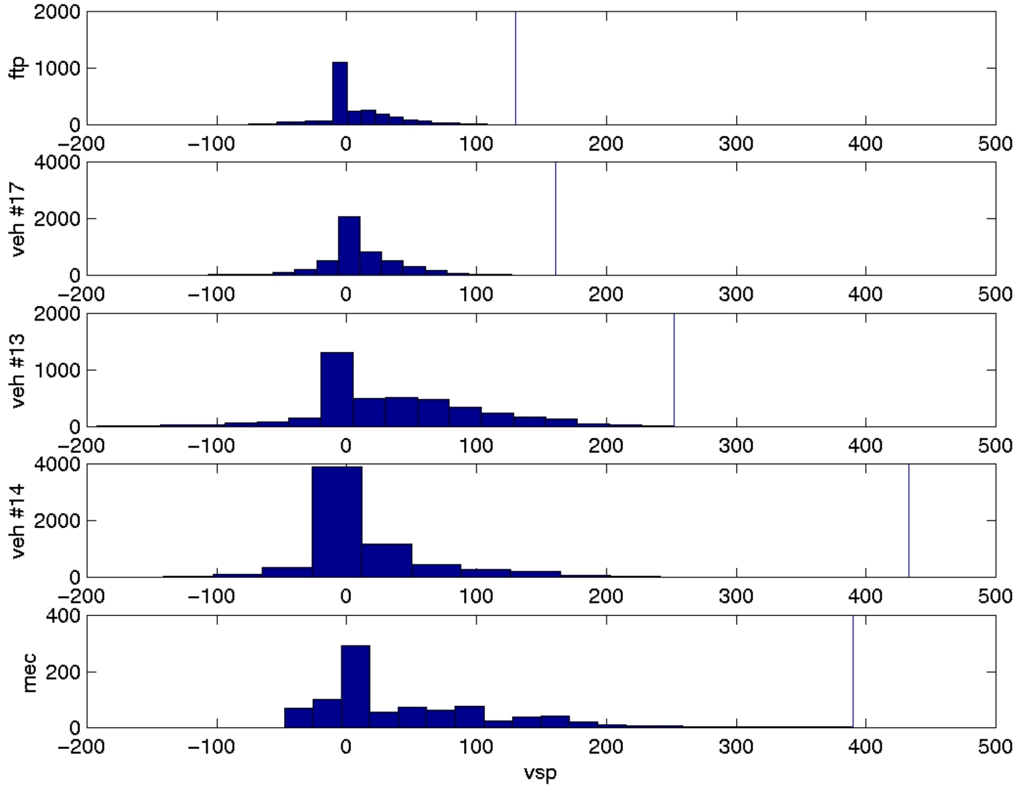

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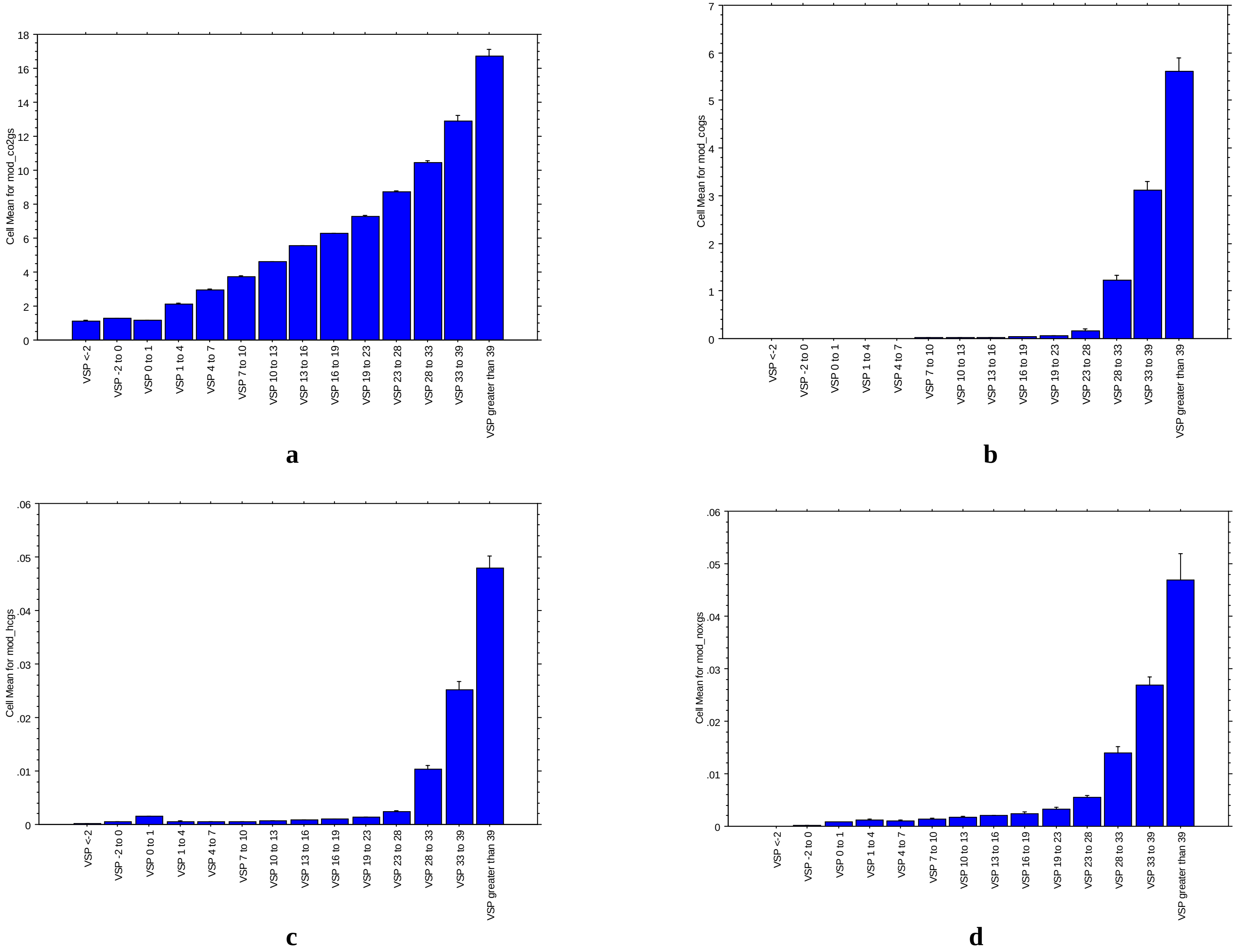
VSP Bin Definition	(VSP in kW/Metric Ton)
1	VSP < -2
2	-2<= VSP <0
3	0<= VSP <1
4	1<= VSP <4
5	4<= VSP <7
6	7<= VSP <10
7	10<= VSP <13
8	13<= VSP <16
9	16<= VSP <19
10	19<= VSP <23
11	23<= VSP <28
12	28<= VSP <33
13	33<= VSP <39
14	39 <= VSP

Table 1: Vehicle Specific Power bins used in preliminary MOVES model *(4)*.



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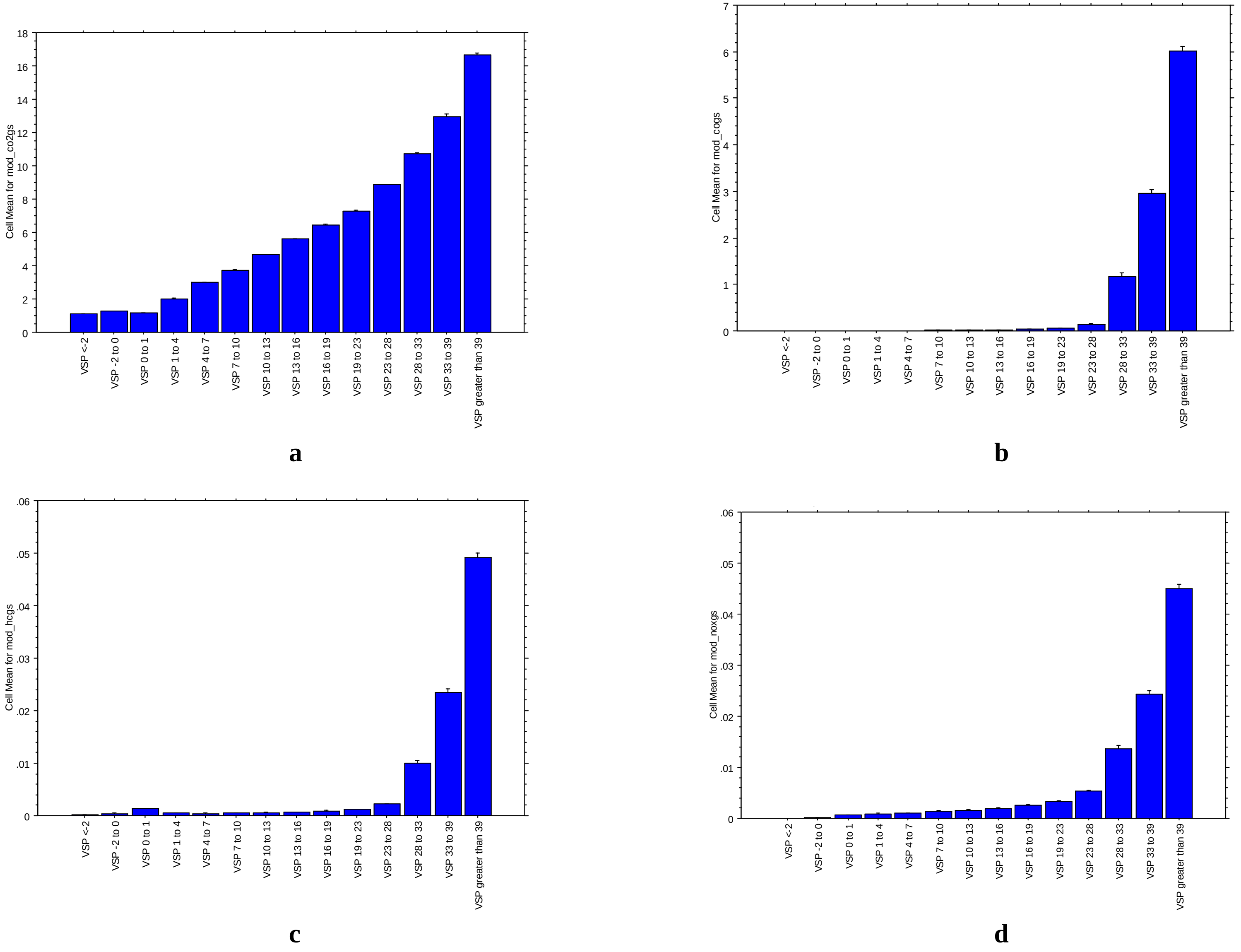

Figure 4: Light-duty emissions (real-world + MEC01 data) as a function of VSP bins defined Table 1. Error bars indicate 95% confidence interval. a) CO_2, b) CO, c) HC, d) NOx

VSP Bin	CO2 Reduction in S.E. (%)	CO Reduction in S.E. (%)	HC Reduction in S.E. (%)	NOx Reduction in S.E. (%)
VSP <-2	50.00%	36.40%	36.67%	36.86%
VSP -2 to 0	25.00%	21.16%	21.05%	21.12%
VSP 0 to 1	0.00%	13.92%	13.77%	14.06%
VSP 1 to 4	22.22%	31.65%	31.78%	31.88%
VSP 4 to 7	18.18%	19.52%	19.55%	19.54%
VSP 7 to 10	7.14%	0.00%	5.00%	5.02%
VSP 10 to 13	28.57%	58.84%	27.79%	27.88%
VSP 13 to 16	20.00%	23.14%	23.37%	24.12%
VSP 16 to 19	20.00%	0.00%	26.48%	27.78%
VSP 19 to 23	12.00%	33.33%	16.01%	17.38%
VSP 23 to 28	34.38%	41.67%	35.52%	40.16%
VSP 28 to 33	29.69%	29.41%	32.69%	61.15%
VSP 33 to 39	39.39%	50.00%	61.28%	58.06%
VSP greater than 39	64.39%	68.09%	53.46%	84.58%

Table 2: Percent reduction in standard error (S.E.) by VSP bin after inclusion of MEC data.

	CO Cycle Estimate Range(%)	
Cycle	On Road Data Only	On-Road Data Augmented
FTP	24.91%	18.40%
MEC	12.06%	5.10%

Table 3: Total cycle CO emissions estimate range (%) by cycle and data.