International Vehicle
Emissions Model

Attachment C
Characterizing Emission Variations due to Driving Behavior from On-Road Vehicles

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1.Overview

Vehicle operating conditions effect emissions by orders of magnitude, and are therefore necessary components in any versatile emissions model. However, the effects of these parameters are extremely difficult to predict. Emissions from vehicle starts are effected not only by the vehicle type, but also by the air temperature, engine temperature and catalyst temperature at the time of start-up. Running emissions are effected by a complex variety of parameters, including but not limited to vehicle speed, acceleration, history, and variations in engine load due to road grade and air conditioning use. Historically, the variation of emissions has been modeled by calculating emissions from a representative driving cycle or set of cycles (CARB 2002). There has been some skepticism and uncertainty in using this methodology, however (EPA 2002 (7 & 8), NRC, 2000). With recent advances in technology, it is now becoming possible to measure on-road emissions, vehicle operating characteristics, and environmental parameters in a resolution that allows for analysis on a second by second basis. This information leads to a novel way of characterizing emissions as a function of a variety of parameters, and is not restricted to a defined set of cycles.

CE-CERT has performed an analysis on a variety of on-road and dynamometer data collected at a minimum of 1 Hz. This data is from the following sources:

- NCHRP data set of over 100 non-catalyst and catalyst light duty vehicles driven on the MEC, FTP and US06 cycles on the dynamometer (Barth 1998),
- On-road PEMS data collected on several Tier 1 light duty vehicles by the EPA (EPA 2002 (8)),
- On-road, track and dynamometer data collected from ULEV and SULEV light duty vehicles as part of the SELEV study (CRC 2003), and
- On-road heavy duty diesel vehicle data from a set of several vehicles collected from (Cocker, 2003).

These were the only appropriate data available at the time of this study. As on-board emissions measurement technology becomes mainstream over the next few years, a more comprehensive data set will be available for analysis. It is with this mentality that the driving behavior module has been developed in the IVE model. The model has been designed to incorporate 60 emissions variations, or ‘bins’, for each technology type. Currently, there is enough statistical variation in emissions to warrant approximately half of these bins. It is hoped that further data will allow for additional resolution of these effects. Described below is the processing and results of this analysis.

2. Data Analysis

An initial analysis was performed on the entire data set to determine the most statistically significant parameters affecting emissions. The variables considered were limited to parameters that would be readily available (or collectable) from vehicles around the world. This excludes any information that could be collected from on-board diagnostics, such as fuel rate and throttle position. The parameters analyzed included velocity, acceleration, rate of change of acceleration, implied rpm (estimated from vehicle speed), and average velocity over a period directly preceding the current time (i.e. history effects). Road grade was estimated by taking a 5 second average road grade. Grades larger than 14% and road grades at velocities of less than 1 kph were filtered out.

It was determined from this data set that the single most important parameter for determining emissions is the vehicle specific power (VSP), which is derived from the instantaneous velocity and acceleration. Recent work conducted by the EPA arrived at a similar conclusion (EPA 2002 (7)). The equation for VSP (kW/ton), first developed for this application by Jimenez-Palacios, is shown in Equation 1 (Jimenez-Palacios 1999).

$$\mathrm{VSP} = v[1.1a + 9.81\,(\mathrm{atan}(\sin(\mathrm{grade}))) + 0.132] + 0.000302v^3 \qquad \text{(Eq. 1)}$$

$\mathrm{grade} = (h_{t=0} - h_{t=-1}) / v_{(t=-1\mathrm{to}0)}$
v = velocity (m/s)
a = acceleration (m/s^2)
h = Altitude (m)

This data shows that vehicle power-based emissions estimates perform quite well for CO_2, but improvements in predictive power for other emissions such as CO, HC, NO_x, and NH_3 may be achieved through the addition of one or more dimensions to the matrix binning approach. In this analysis, a parameter called engine stress is used in addition to VSP. Engine stress was shown to correlate best to vehicle power load requirements over the past 20 seconds of operation and implied engine RPM (Eq. 2, Table 1). Low engine stress refers to conditions in which vehicle operation has encountered low speed and accelerations over the last 20 seconds of operation and the engine RPM is relatively low, and high engine stress occurs at high speed and accelerations over the most recent 20 seconds and engine RPM is high. A total of 60 bins for the VSP/stress categories were used for this analysis (Table 2).

$$\text{Engine Stress } \mathit{(unitless)} = \mathit{RPMIndex} + \mathit{(0.08\ ton/kW)*PreaveragePower} \qquad \text{(Eq. 2)}$$

$\mathit{PreaveragePower} = \mathit{Average}(\mathit{VSP}_{t=-5sec\ to\ -25\ sec})\ \ (kW/ton)$
$\mathit{RPMIndex} = \mathit{Velocity}_{t=0}/\mathit{SpeedDivider}\ \ (unitless)$
$\mathit{Minimum\ RPMIndex} = 0.9$

Table 1. Cutpoints used in *RPMIndex* Calculations

Speed Cutpoints (m/s)		Power Cutpoints (kW/ton)		Speed Divider (s/m)
Min	Max	Min	Max	
0.0	5.4	-20	400	3
5.4	8.5	-20	16	5
5.4	8.5	16	400	3
8.5	12.5	-20	16	7
8.5	12.5	16	400	5
12.5	50	-20	16	13
12.5	50	16	400	5

Table 2. Boundaries Assumed in VSP/Engine Stress Binning

	VSP (kW/Ton)		Engine Stress	
Bin	Lower	Upper	Lower	Upper
0	-80.0	-44.0	-1.6	3.1
1	-44.0	-39.9	-1.6	3.1
2	-39.9	-35.8	-1.6	3.1
3	-35.8	-31.7	-1.6	3.1
4	-31.7	-27.6	-1.6	3.1
5	-27.6	-23.4	-1.6	3.1
6	-23.4	-19.3	-1.6	3.1
7	-19.3	-15.2	-1.6	3.1
8	-15.2	-11.1	-1.6	3.1
9	-11.1	-7.0	-1.6	3.1
10	-7.0	-2.9	-1.6	3.1
11	-2.9	1.2	-1.6	3.1
12	1.2	5.3	-1.6	3.1
13	5.3	9.4	-1.6	3.1
14	9.4	13.6	-1.6	3.1
15	13.6	17.7	-1.6	3.1
16	17.7	21.8	-1.6	3.1
17	21.8	25.9	-1.6	3.1
18	25.9	30.0	-1.6	3.1
19	30.0	1000.0	-1.6	3.1
20	-80.0	-44.0	3.1	7.8
21	-44.0	-39.9	3.1	7.8
22	-39.9	-35.8	3.1	7.8
23	-35.8	-31.7	3.1	7.8
24	-31.7	-27.6	3.1	7.8
25	-27.6	-23.4	3.1	7.8
26	-23.4	-19.3	3.1	7.8
27	-19.3	-15.2	3.1	7.8
28	-15.2	-11.1	3.1	7.8
29	-11.1	-7.0	3.1	7.8
30	-7.0	-2.9	3.1	7.8
31	-2.9	1.2	3.1	7.8
32	1.2	5.3	3.1	7.8
33	5.3	9.4	3.1	7.8
34	9.4	13.6	3.1	7.8
35	13.6	17.7	3.1	7.8
36	17.7	21.8	3.1	7.8
37	21.8	25.9	3.1	7.8
38	25.9	30.0	3.1	7.8
39	30.0	1000.0	3.1	7.8
40	-80.0	-44.0	7.8	12.6
41	-44.0	-39.9	7.8	12.6
42	-39.9	-35.8	7.8	12.6
43	-35.8	-31.7	7.8	12.6

Table 2. Boundaries Assumed in VSP/Engine Stress Binning, Cont.

	VSP (kW/Ton)		Engine Stress	
Bin	Lower	Upper	Lower	Upper
44	-31.7	-27.6	7.8	12.6
45	-27.6	-23.4	7.8	12.6
46	-23.4	-19.3	7.8	12.6
47	-19.3	-15.2	7.8	12.6
48	-15.2	-11.1	7.8	12.6
49	-11.1	-7.0	7.8	12.6
50	-7.0	-2.9	7.8	12.6
51	-2.9	1.2	7.8	12.6
52	1.2	5.3	7.8	12.6
53	5.3	9.4	7.8	12.6
54	9.4	13.6	7.8	12.6
55	13.6	17.7	7.8	12.6
56	17.7	21.8	7.8	12.6
57	21.8	25.9	7.8	12.6
58	25.9	30.0	7.8	12.6
59	30.0	1000.0	7.8	12.6

3. Results of Emissions Binning

The data was categorized into five vehicle groups:

- closed-loop catalyst equipped gasoline vehicles,
- closed loop non-catalyst gasoline vehicles,
- carbureted catalyst equipped gasoline vehicles,
- carbureted non-catalyst gasoline vehicles, and
- all diesel vehicles.

For each group, the average second-by-second emissions in each stress and power bin was estimated from the available data. The total emissions from bag 2 and 3 of the FTP for each vehicle category was used to normalize emissions in every power bin. Figures 1-5 illustrate how these normalized emissions vary with vehicle specific power and engine stress. For all pollutants, the emissions rise with an increase in both vehicle specific power and engine stress. The greatest increase is typically seen for CO, and for closed-loop catalyst- equipped vehicles. Note that the diesel vehicles do not show the wide variation in CO emissions seen in gasoline vehicles, but trends for the other pollutants are similar.

CO_2, VOC, NOx and CO were the only four pollutants modeled in this manner, due to the lack of availability of second by second data for the other pollutants. Therefore, assumptions were made for the remaining pollutants as to the effect of driving behavior. SOx, Pb and N_2O driving effects were modeled after the patterns observed for CO_2, while the toxics and methane were assumed to behave similarly to VOC emissions. There has been some preliminary research at CE-CERT that indicates that NH_3 and PM emissions act similarly to CO emissions. In addition, assumptions about the remaining technologies, such as alternative fueled vehicles, were made. In general, most alternative fueled vehicles were assumed to have the same corrections as their gasoline counterparts. A map of the driving pattern corrections for each vehicle technology and each pollutant is included in the Driving Pattern Excel workbook, and a description of the codes is listed in Appendix A.

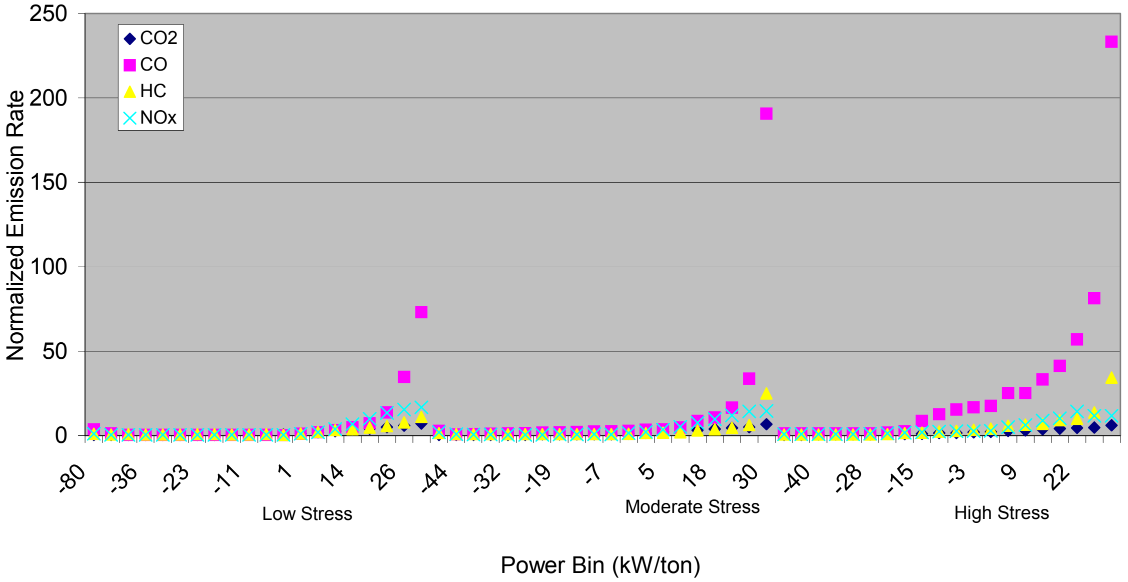

Figure 1. Emissions Variation with Power Bin for Closed Loop, Catalyst Equipped Light Duty Vehicles

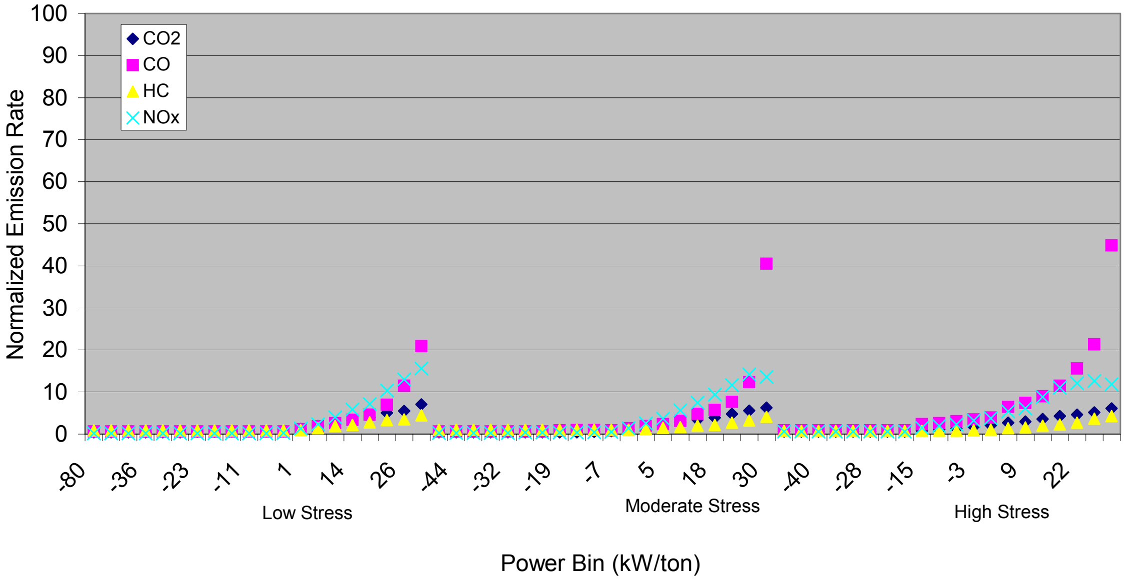

Figure 2. Emissions Variation with Power Bin for Closed Loop, Non-Catalyst Light Duty Vehicles

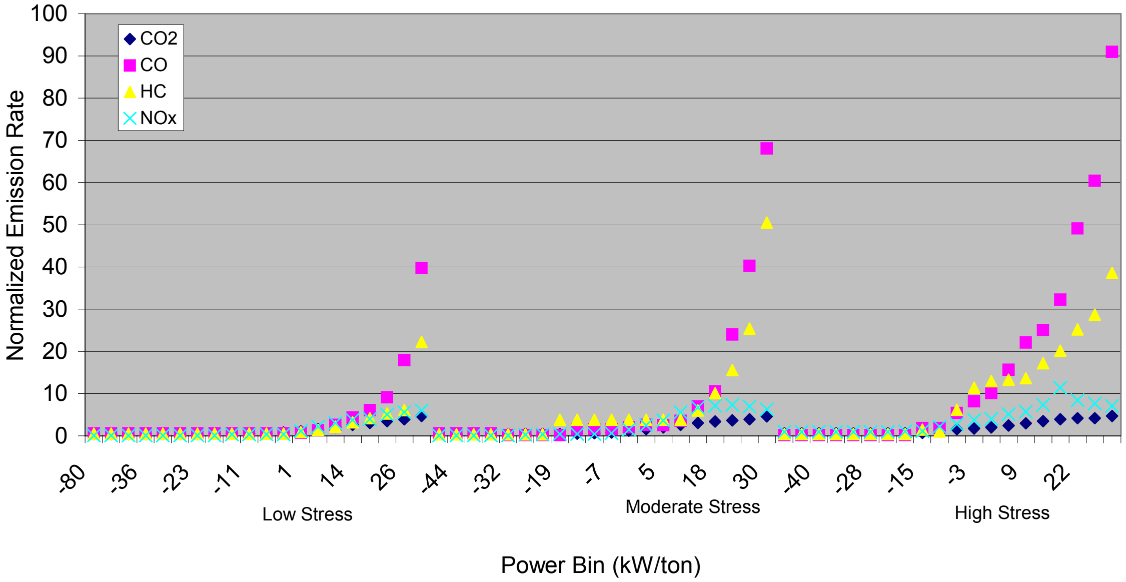

Figure 3. Emissions Variation with Power Bin for Carbureted, Catalyst Equipped Light Duty Vehicles

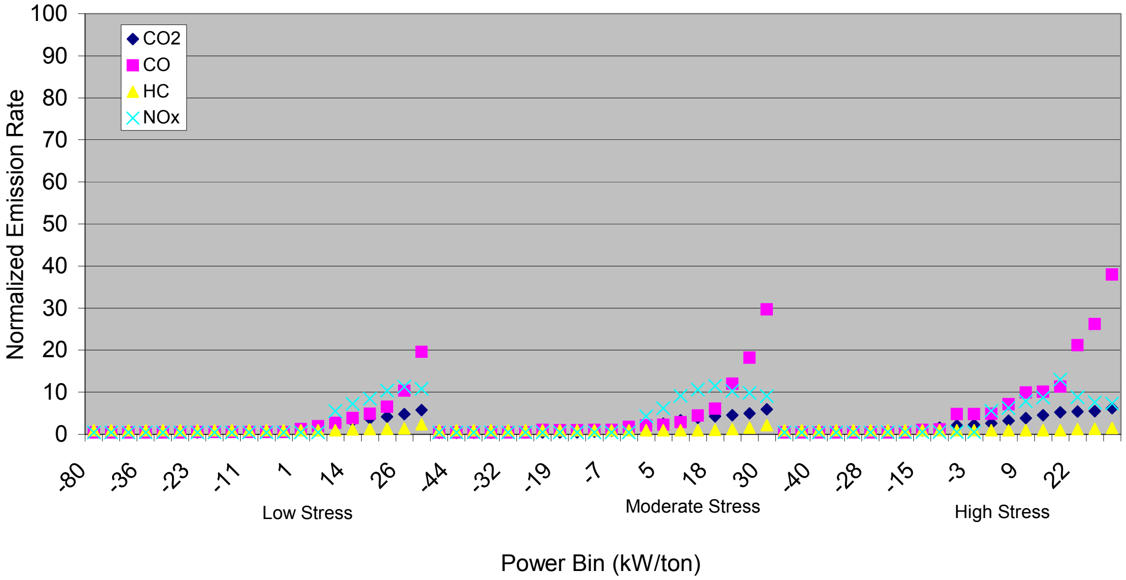

Figure 4. Emissions Variation with Power Bin for Carbureted, Non-Catalyst Light Duty Vehicles

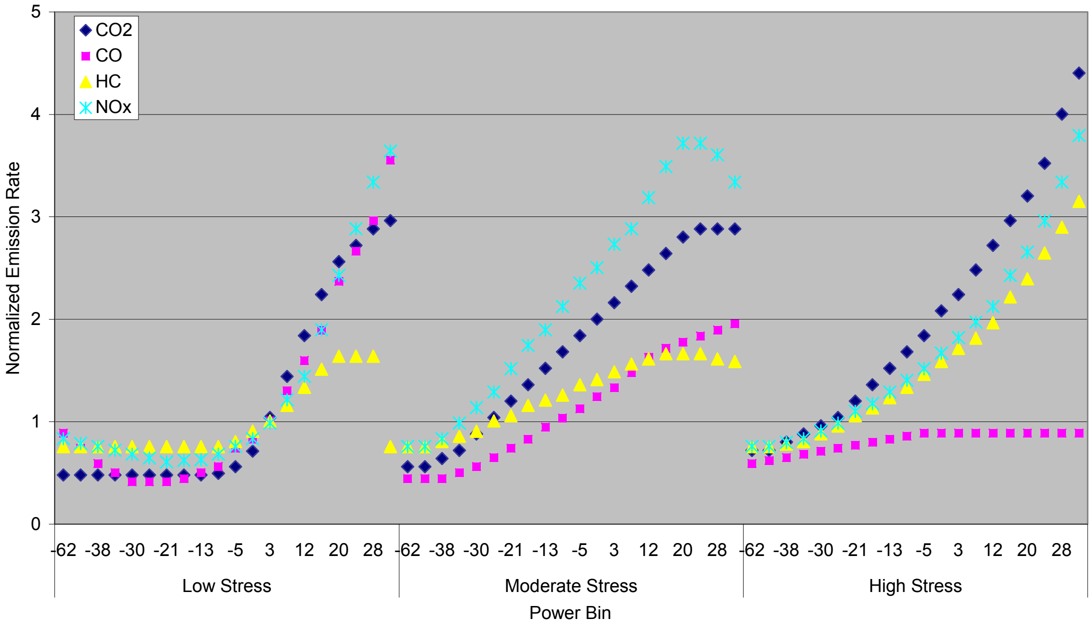

Figure 5. Emissions Variation with Power Bin for Diesel Vehicles

4. Comparison With Other Models

It is useful to compare the effect of these driving corrections to some of the other available models. It is not expected that the IVE and MOBILE6 predictions should be similar since a completely different approach and data sources were used for their development. However, it is useful to see these differences to understand the variation in emissions under different methodologies and also for consideration when comparing the models in overall validation exercises. It is also valuable to see how other models using cycle and modal method compare with the IVE and MOBILE models. Two other models were used for this comparison, ARB's EMFAC2002 model, and the University of California's Comphrensive Model Emissions Model (An 2000). EMFAC2002 is the California Air Resources Boards most recent mobile source emissions inventory model (ARB, 2002). The CMEM model is designed primarily to compare emissions differences on microscale level of driving behavior, and because it uses a unique modal approach to modeling driving behavior is a useful comparison of effects of driving changes.

To illustrate the driving corrections from the various models, emissions were predicted on five different driving cycles and two technology types. Table 3 briefly describes these five cycles developed by Sierra Research (EPA 1997). Figures 6-11 below display the results of emissions from different vehicle types for the four models. The first bar represents the emissions from the facility cycle Arterial CD, normalized (divided) by the emissions from facility cycle Arterial AB. Then there are bars displaying the cycles Arterial EF, Freeway AC, and Freeway F, all normalized to the emissions from Arterial AB cycle. The further a value is from one, the more significant the predicted impact is of the current drive cycle.

For example, in Figure 6, the cycle Arterial EF predicted by the CMEM model has the most profound increase in emissions for all of the cycle and models analyzed. It is measured to be over 1.8 times higher emissions than measured on the Arterial AB driving cycle.

Table 3. Description of Driving Cycles Used in the Model Comparison

Facility Cycle	Description	Average Speed (kph)	Maximum Speed (kph)	Maximum Acceleration (kph/s)	Length (sec)	Length (km)
ArtAB	Arterial Roadway with freeflow traffic	39.9	94.8	8.0	737.0	8.2
ARTCD	Arterial Roadway with moderate traffic congestion	30.9	79.7	9.2	629.0	5.4
ARTEF	Arterial Roadway with heavy traffic congestion	18.7	64.2	9.3	504.0	2.6
FWYAC	Freeway with freeflow traffic	96.1	117.6	5.5	516.0	13.8
FWYF	Freeway with heavy traffic congestion	29.9	80.3	11.1	442.0	3.7

These figures show that driving patterns effect emissions from individual technologies and pollutants differently. In general, all four models show similar trends, with some exceptions. Generally, the CMEM and IVE models predict a larger effect from driving pattern variations than the MOBILE and EMFAC models. The IVE and CMEM models show similar trends in CO emissions variation with driving variations for gasoline vehicles, although the CMEM model predicts the largest CO variation of all models. For HC, the lowest emissions are consistently from the high speed highway cycle. For non-catalyst vehicles, the CMEM, IVE and MOBILE models show the highest emissions from a congested arterial cycle. For catalyst vehicles, these three models show the highest emissions occurring during either the congested arterial or the high speed freeway cycle.

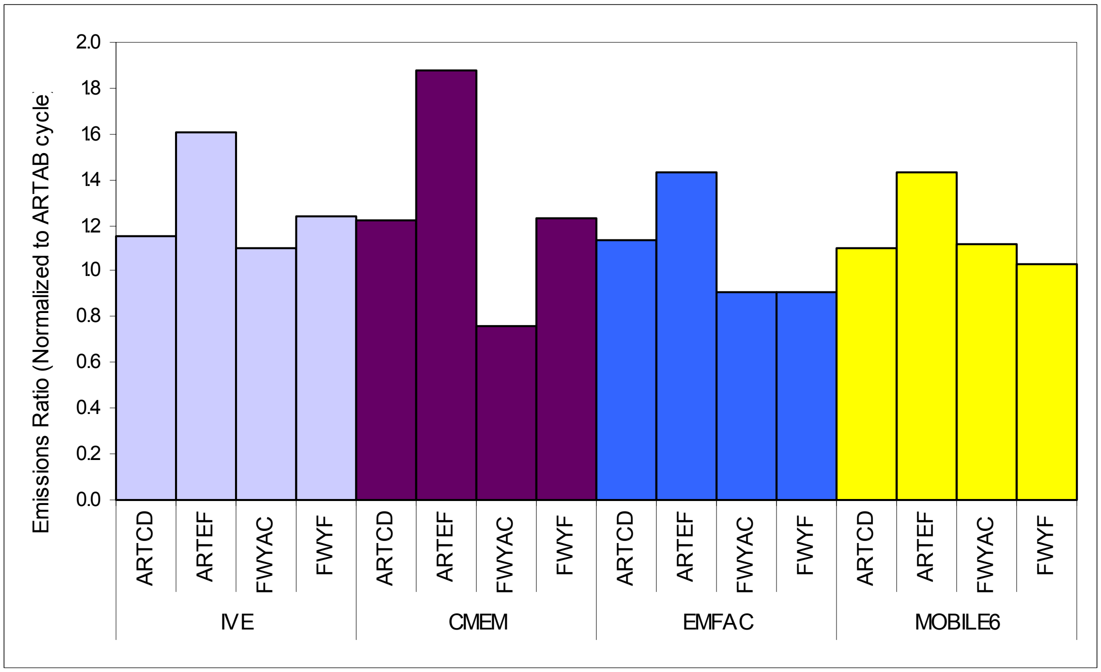

Figure 6. Effect of Driving Behavior on CO Emissions from Four Different Models for Carbureted, Non-Catalyst Light Duty Vehicles

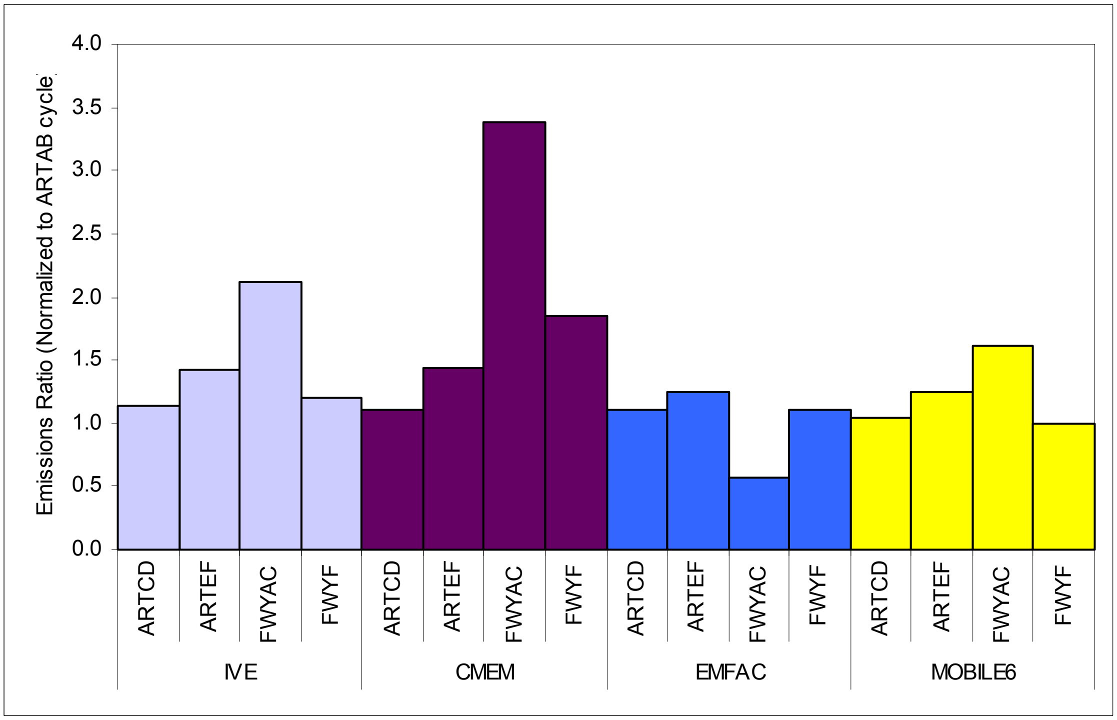

Figure 7. Effect of Driving Behavior on CO Emissions from Four Different Models for Tier 0 Light Duty Vehicles

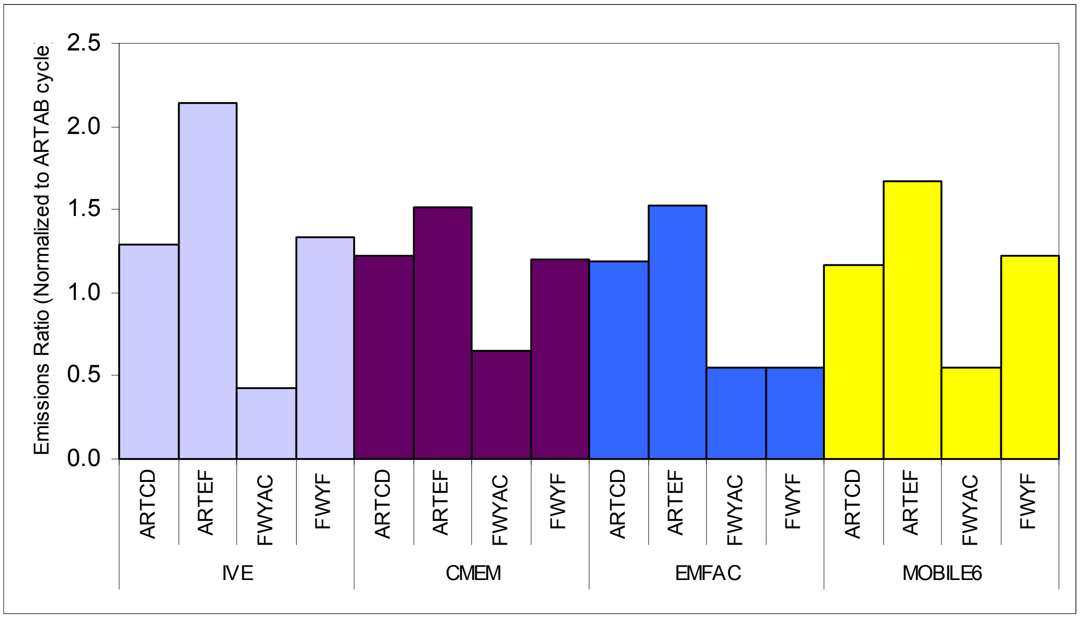

Figure 8. Effect of Driving Behavior on HC Emissions from Four Different Models for Carbureted, Non-Catalyst Light Duty Vehicles

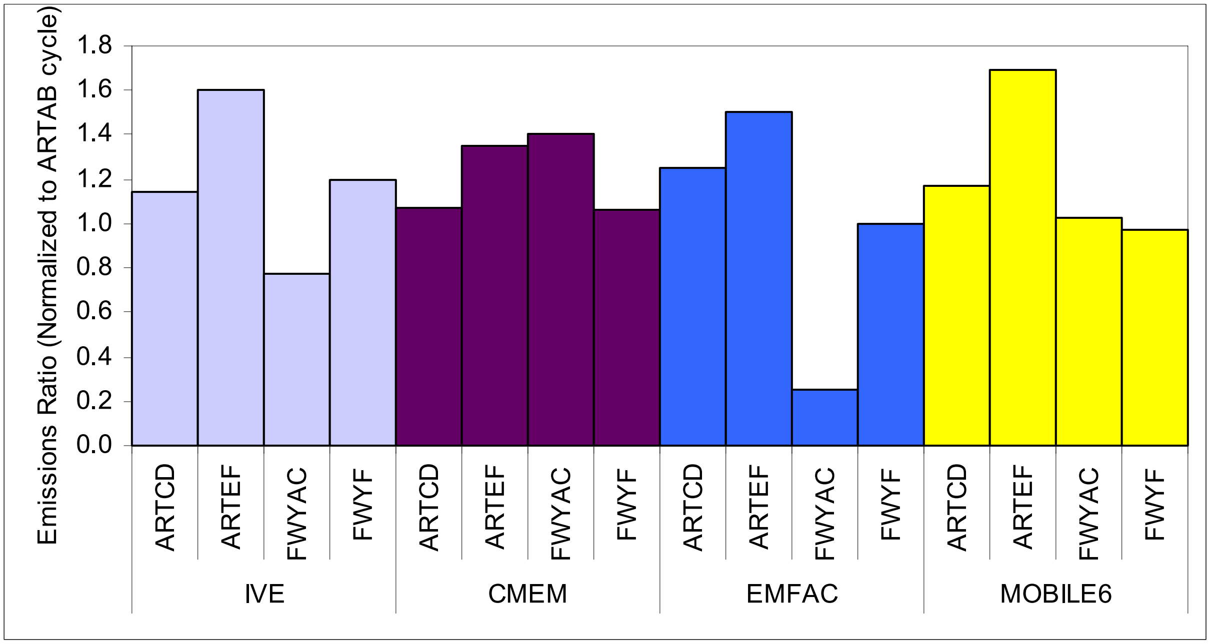

Figure 9. Effect of Driving Behavior on HC Emissions from Four Different Models for Tier 0 Light Duty Vehicles

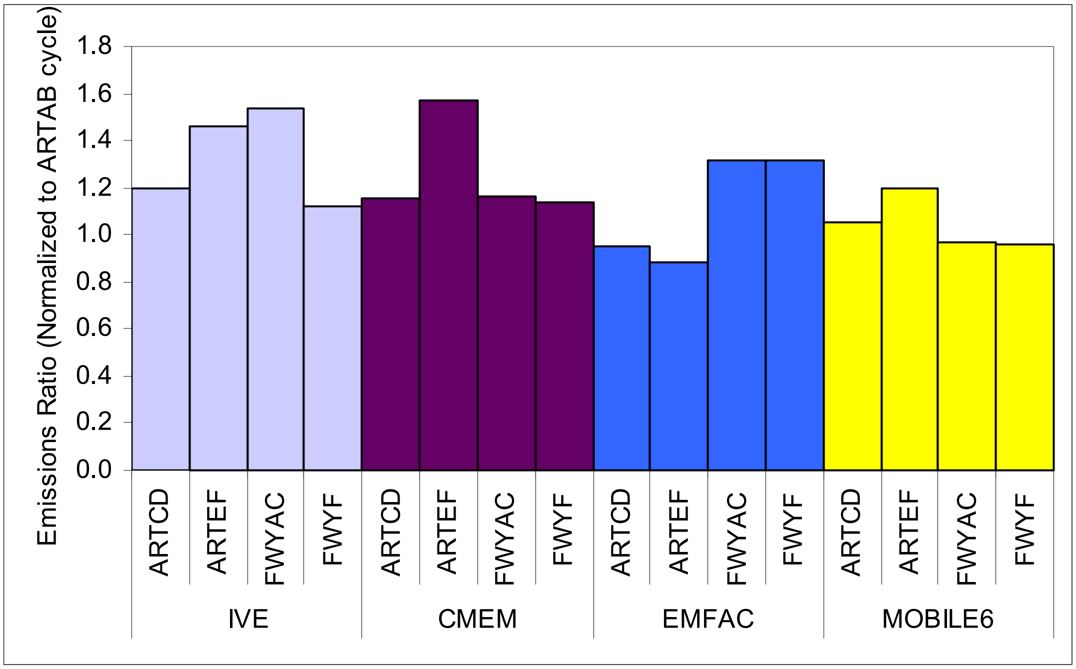

Figure 10. Effect of Driving Behavior on NOx Emissions from Four Different Models for Carbureted, Non-Catalyst Light Duty Vehicles

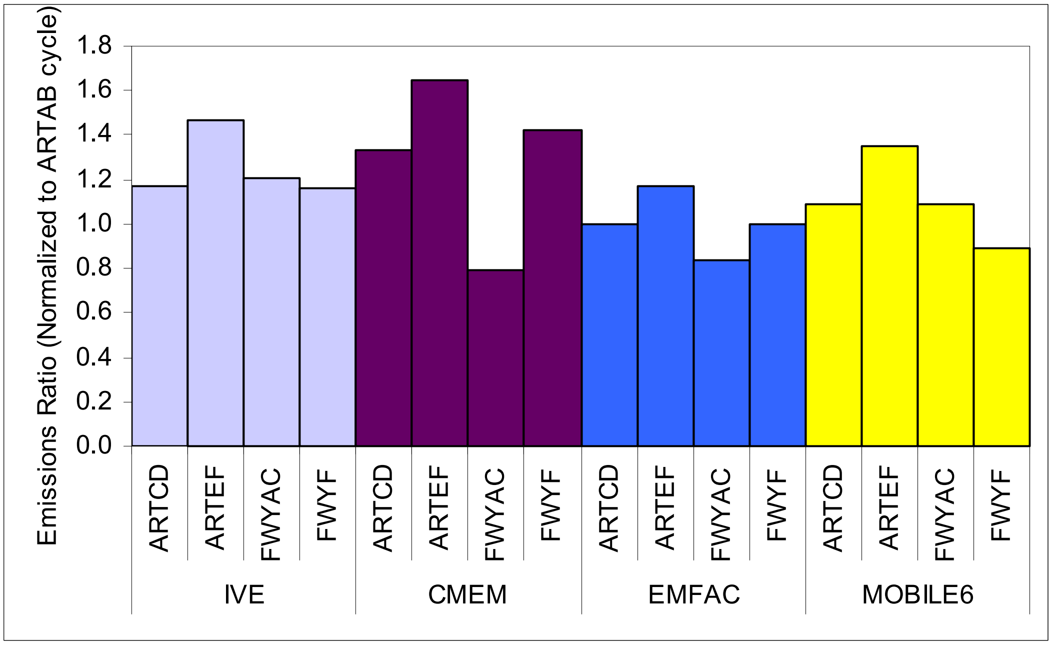

Figure 11. Effect of Driving Behavior on NOx Emissions from Four Different Models for Tier 0 Light Duty Vehicles

5. Application

Vehicle emissions estimates can be calculated by referencing the observed VSP on a second-by-second basis to the emissions rates calculated from the model development data within the bins. The advantage of the binning approach allows for any driving cycle to be captured by altering the frequency in each condition and eliminates the need for a representative cycle to be developed. The frequency distribution in each bin will change with various roadways, drivers, level of congestion, and location, and therefore change the emissions associated with each type of driving. The vehicle activity for any city can be easily measured using CGPS instrumentation (IVE 2003).

Figure 12. shows the frequency distribution for a typical freeway, arterial, and residential driving conducted in Los Angeles, CA. This data was collected in the SELEV study using GPS technology in the Summer of 2001.

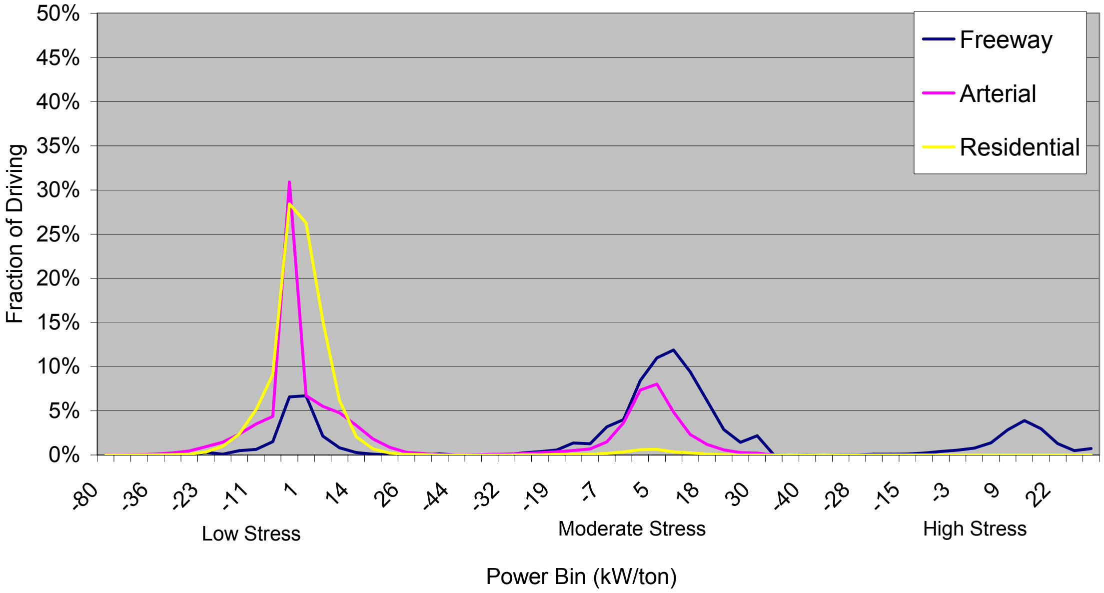

Figure 12. Travel Frequency Distribution by Power Bin for Various Roadways in Los Angeles, California

The frequency distribution collected in this area can be applied to the emissions in each driving bin for estimating emissions for the overall driving. From this analysis, it is clear that emissions from the residential driving trace are in general most similar to emissions from the LA4 cycle. The effects of the high stress and high VSP driving observed in the freeway cycle in Figure 16 is reflected in the high CO emissions from this cycle in Figure 13.

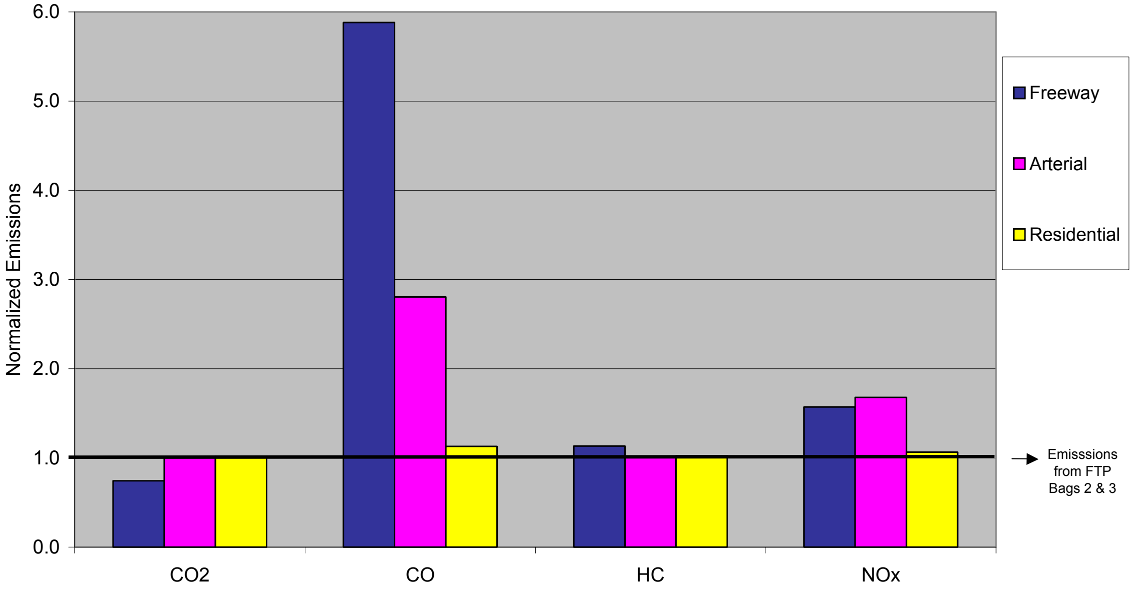

Figure 13. Normalized Emissions from Closed Loop, Catalyst Equipped Light Duty Vehicles during Various Types of Driving

The same driving patterns may be applied to the other vehicle technologies. Each frequency distribution supplied by the user is applied to the emissions corrections determined in this paper, resulting in an average emissions per distance or time driven. For information on how to input the percentage of driving in each bin, refer to the main portion of the User’s Guide.

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Appendix A.
Driving Pattern Map Used for All Technologies and Pollutants in the IVE Model

Table A.1 Code for Deciphering Driving Pattern Map

	Number Before Decimal (#.#)	Number After Decimal (#.#)
Value	Technology	Pollutant
0	carbureted non-catalyst gasoline vehicles	CO
1	carbureted catalyst equipped gasoline vehicles	VOC
2	closed loop non-catalyst gasoline vehicles	n/a
3	closed-loop catalyst equipped gasoline	NOx
4	Diesel vehicle	CO2

Example: a value of 1.3 would indicate the pollutant driving corrections used were based on NOx emissions from a carbureted catalyst equipped gasoline vehicle.