Development of a Modal Emissions Model Using Data from the Cooperative Industry/Government Exhaust Emission Test Program

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ABSTRACT

The Environmental Protection Agency's (EPA's) recommended model, MOBILE5a, has been used extensively to predict emission factors based on average speeds for each fleet type. Because average speeds are not appropriate in modeling intersections or other scenarios involving intermittent travel, emission factors that are specific for vehicle operating modes (acceleration, deceleration, free-flow, and idle) have been studied in the past. Several models have been developed that use the concept of acceleration-speed products to serve as input variables to determine multipliers that can be used to modify constant speed emission factors. Although relatively simplistic, this process provides results that are considered more accurate than constant speed emission factors. The Comprehensive Modal Emissions Model (CMEM) developed under sponsorship by the National Cooperative Highway Research Program (NCHRP) is based on a parameterized physical approach. While anticipated to be more accurate, the input requirements to the model are necessarily more complicated.

This paper presents a new modal emissions model based on existing emissions data from the early 1990s revision efforts of the Federal Test Procedure (FTP). The model updates the older acceleration-speed product models that were based on data from the 1970s. Using second-by-second emissions data, several different forms of the modeling equations were developed and statistically analyzed for predicting multiplying factors for CO. A goal in developing this model is to serve as a comparison basis for the NCHRP model. The second and more

important goal is to use the model as part of a microscale traffic simulation model that predicts air quality near roadways.

INTRODUCTION

A new vehicle emissions model has been developed at the University of Central Florida (UCF) to predict vehicle emissions that are specific to operating modes (e.g. idle, cruise, acceleration, and deceleration). This modal emissions model uses the product of speed and acceleration as the input variable and a modal multiplier as the independent variable. The modal multiplier is used to convert a constant speed emission factor for Carbon Monoxide (CO), such as that obtained from the MOBILE series models, into a modal emission factor.

The new model updates and expands upon previous models by using emissions data from the 1993-1994 tests conducted at the General Motors Proving Ground (1). The other models use older databases, typically gathered in the 1970s. A goal in developing the model was to serve as a comparison for existing modal emission models including the Comprehensive Modal Emissions Model (CMEM) developed at the University of California at Riverside (UCR) under sponsorship by the National Cooperative Highway Research Program (NCHRP) (2). However, the main reason was to use the model as part of an overall air quality model that predicts CO concentrations near roadways (3). This air quality model, also developed at UCF, uses a microscale traffic movement algorithm and Gaussian puff equations to model each vehicle as a moving point source. This simulation approach requires a model that can provide second-by-second modal emission factors. Although CMEM can produce second-by-second emission factors, its use in the air quality model would be difficult partly due to data requirements, but also because the CMEM software was not designed to be used in a simulation environment. However, it may be possible to incorporate the main CMEM code(s) into the air quality model such that communication between the two is internal rather than through input and output files. Due to time constraints, CMEM incorporation into the air quality model is beyond the scope of this project and is a consideration for future work.

BACKGROUND

Emission models have typically been based on regressions of emissions data collected for driving cycles such as the Federal Test Procedure (FTP). Since the condition of a vehicle in the hot and cold stabilized phases are considered to be similar, bag 4 measurements are usually not taken. The basic emission rate (BER) determined by the EPA recommended MOBILE series models is weighted by using the default start mode fractions of 0.43 for cold start and 0.57 for hot start conditions. The emission rates determined by these models are based on average speeds for each fleet type. Because average speeds are not appropriate in modeling intersections or other scenarios involving intermittent travel, emission factors that are specific for vehicle operating modes (acceleration, deceleration, free-flow, and idle) have been studied.

In the past, several models have been developed that use the concept of speed-acceleration products to serve as input variables to determine multipliers that can be applied to constant speed emission factors. The reasoning behind this approach is that vehicles are assumed to accelerate at a constant rate of power input. This translates into the product of speed and acceleration being equivalent to power divided by mass which can easily be proven by unit analysis. Therefore, the underlying thought is that as the speed-acceleration product, and hence, power demand increases, so will the emission rate for CO (4).

One of the studies was performed by the Colorado Department of Highways (CDOH) (4). They developed a relatively simple model to predict the multipliers that could be used to convert constant speed emission factors to modal emission factors. A multiplier is actually a normalized value derived by dividing a vehicle's emission rate for a particular modal activity (i.e. combination of acceleration and speed of vehicle) by its average 75 FTP emission rate. Using a total of 45 vehicles (1975 model year) and 39 modal activities in the Surveillance Driving Sequence (SDS) for each vehicle, best fit curves for the data were developed that correlate multipliers for CO, HC, and NO_x with the product of speed and acceleration. The corresponding quadratic equation for CO is presented below:

$$M = 0.182 - 7.9776 \times 10^{-3} (AS) + 3.6227 \times 10^{-4} (AS)^2 \qquad (1)$$

M = multiplier for CO

AS = speed-acceleration product (ft^2/sec^3)

Since the emission rate and the speed-acceleration product are believed to be linearly related, the second order term in equation 1 has been attributed to factors such as the air/fuel mixture enrichment under load and reaching the limits of the catalytic converter. Due to the fact that the modal emission rates were normalized with respect to the 75 FTP rate obtained from bag data, the multipliers are only applicable to emission factors based on a constant speed of 19.6 mph which is the average speed for the 75 FTP cycle.

The CALINE4 model uses a similar approach to determining multipliers. However, the data sets used to derive regression equations were different than the ones use in the CDOH study. CALINE4 uses data specific to California (5). The two equations employed in CALINE4 are presented as equations 2 and 3:

$$EFA = (BAG2)(0.75)e^{(0.0454)(AS)} \qquad (2)$$

$$EFA = (BAG2)(0.027)e^{(0.098)(AS)} \qquad (3)$$

EFA = modal emission factor

BAG2 = constant speed emission factor

Equation 2 is applicable for vehicles accelerating from rest to 45 mph, and equation 3 corresponds to vehicles accelerating from speeds greater than 15 mph to 60 mph. These equations are similar to the CDOH equation except that the constant speed emission factor (BAG2) has been included so that the equations represent modal emission factors rather than a multiplying factor. Unlike the CDOH model, CALINE4 uses only bag 2 (stabilized mode) emissions data to derive the multipliers. Therefore, CALINE4 requires that constant speed emission factors be based at 16.2 mph which is the average speed for the bag 2 stage of the FTP cycle.

The new NCHRP model (CMEM) is based on a parameterized physical approach (2). While anticipated to be more accurate than the speed-acceleration product approach, the input requirements are also more involved. The inputs for this model can be grouped into two broad categories: input operating variables and model parameters. Examples of input operating variables include second-by-second speed, grade, and accessory use information (e.g. air conditioning). Model parameters include public domain or generic types (e.g. vehicle mass, engine displacement, tire rolling resistance, transmission efficiencies, etc.) and measured types (e.g. engine friction factor, thermal efficiency, catalyst pass fraction, etc.). The model not only determines composite emission factors but also provides second-by-second tailpipe emissions. The current condition of the software does not realistically allow it to be used in a simulation environment where function calls to CMEM would have to be made during each simulated time step. Therefore, the core algorithm in CMEM would need to be reproduced and implemented internally for it to be used in an air quality model that requires modal emission factors during a simulation.

METHODOLOGY

The development of modal multipliers is based on the comprehensive emissions data from the 1993-1994 tests conducted at the General Motors Proving Ground. The tests arose out of efforts to review and revise the FTP and was jointly executed by the EPA, the California Air Resources Board (CARB) and the automotive industry. For simplicity, this cooperative industry/government exhaust emissions data will henceforth be referred to as the CIGEE data which includes both cumulative bag data and second-by-second emissions data for several different test cycles.

The method of analysis essentially mirrors those used in the CDOH and CALINE4 studies. Second-by-second emissions data are correlated with the products of average speeds and accelerations. The steps involved in determining multipliers are outlined in Figure 1. Only the CIGEE data corresponding to the FTP test cycle (also known as the LA4) was used. A total of 83 possible acceleration/deceleration ranges were identified from this cycle. A difficulty in developing these ranges was that the ranges for each tested vehicle did not perfectly correlate time-wise with those for the others. This is understandable since tolerances along the speed versus time curve are allowed during the FTP test. Since the differences between these ranges were small, the derived acceleration values from each vehicle were considered comparable to those from other vehicles. The list of speed ranges shown in Table 1 were derived based on the requirements that the ranges are common to all vehicles tested and that the list contains a sufficient mixture of speed ranges producing varying acceleration values. Such a list is similar to the lists of SDS modes used in the CDOH and CALINE4 studies. Speed ranges corresponding to deceleration were not used since it was assumed that emissions during deceleration are similar to idle emissions. Also, any emissions data corresponding to vehicles that were calibrated for stoichiometric combustion were eliminated since they would not allow those vehicles to produce emissions under commanded enrichment. Stoichiometric calibration was done for some vehicles in order to compare them with production vehicles experiencing commanded enrichment.

The most significant difference between the new emissions model and the previously developed models is that the hot and cold mode percentages were incorporated into the new model. Using composite bag data, separate equations were developed for vehicles in the hot transient, cold transient, and stabilized modes. In order to use these equations, constant speed emission rates specific to each of the modes must be determined. If using MOBILE5a, these hot, cold, and stable emission rates can be determined by using the percentages shown in Table 2. These rates can be considered "pure" since the percentages in Table 2 force MOBILE5a to produce unweighted, bag-specific values. In addition to modal activity, equations were also categorized by vehicle type. The descriptions of each vehicle type and vehicle information are presented in Table 3. Since the CIGEE database did not include heavy-duty vehicles, no equations for this vehicle-type could be developed.

RESULTS

The modal multiplier regression coefficients and goodness of fit criteria are presented in Table 4. The model types are presented as equations 4-6:

Polynomial: $$y = ax^2 + bx + c \tag{4}$$

Power Series: $$y = ax^b \tag{5}$$

Exponential: $$y = ae^{bx} \tag{6}$$

The coefficients in Table 4 indicate that for the stabilized modes, the regression equations increase with the product of speed and acceleration. This is the opposite case for the transient (hot and cold) modes. The reasons for the decreasing functions are not clear since several factors could account for this. One reason may be that a few non-representative data points (i.e. outliers) may have skewed the results. Another reason may be that for the vehicles tested, increasing the speed of the vehicles under transient conditions could have improved engine combustion (e.g. by increasing engine temperature) resulting in lower CO emisisons. This effect could have overcome the effect of increasing CO emissions from an increase in fuel consumption (i.e. enrichment of the air-fuel mixture).

Except for cars and heavy-light trucks under the stabilized condition and light trucks under the hot transient condition, the coefficient of determination (R^2) appears reasonable for most of the regression results. The root MSEs appear to be relatively small for most of the models except for those in the cold transient mode. However, all of their p-values are well below the significance level of 0.05 (95% confidence). Taking into account all of the goodness of fit criteria, the recommended equations for combinations of vehicle type and mode are indicated in bold in Table 4 and plotted in Figures 2-4.

In an effort to compare the current model with existing models, the model developed for "cars" under stabilized conditions was plotted against the models used in CALINE4 and CMEM (NCHRP model). In order to simplify the comparisons, only the regression equations for the stabilized (bag 2) phase were used. Since this phase of the FTP cycle starts from the rest condition (0 mph), the appropriate CALINE4 equation was used:

$$EFA = (BAG2)(0.75)e^{(0.0454)(AS)} \tag{7}$$

This equation corresponds to vehicles starting from rest and accelerating up to 45 mph. Since modal multipliers were modeled, the actual equation used to represent CALINE4 was:

$$M = EFA/BAG2 = (0.75)e^{(0.0454)(AS)} \tag{8}$$

Since CMEM does not contain regression equations to directly provide modal multipliers, the velocity activity data for the FTP bag 2 phase was used to run CMEM and obtain second-by-second emissions data. The default vehicle parameter data supplied with the CMEM software was used during the run. The second-by-second emissions data was used to obtain average emission rates (g/s) for each of the selected speed ranges in the stabilized mode shown in Table 1. Dividing these rates by the average emission rate (converted to g/s by multiplying g/mile by the average speed, 16.2 mph) for the stabilized phase resulted in modal multipliers. Regression analysis of the multipliers with the product of speed and acceleration resulted in equation 9.

$$M = (0.919)e^{(0.0461)(AS)} \tag{9}$$

The plots of each of the three models are shown in Figure 5. The model developed using the CIGEE data provided the highest values and therefore, appears to be the most conservative. This model corresponds to the cars ("C") category and is presented as equation 10.

$$M = (1.300)e^{(0.0430)(AS)} \tag{10}$$

The ratio between the CIGEE multipliers and the CALINE4 multipliers decreases from 1.73 at 1 mph to 1.58 at 45 mph. Similarly, the CIGEE multipliers to CMEM multipliers range from 1.40 at 1 mph to 1.24 at 45 mph. While these comparisons are valid for CALINE4, they may not be entirely accurate for CMEM. The aforementioned regression analysis using the second-by-second emissions output from CMEM only involved one vehicle's parameter data (i.e. default data). This was done due to a lack of data. Therefore, a more comprehensive study would involve the use of several different vehicle parameter data to obtain a more statistically valid regression equation. An alternative but equal method of comparison between the models would have involved the plotting of actually emission values instead of multipliers. But since the multipliers and emission rates are directly related, the results would have led to similar conclusions.

CONCLUSION

The new modal emissions model presented in this paper is an update to the older emissions models developed by the CDOH and CALINE4 studies. The use of modal multipliers is significantly different than the physical modeling approach employed in the NCHRP model (CMEM). A simple comparison analysis appears to indicate that the new model provides similar results to that of CMEM. The simplicity of the new model allows easy integration into a traffic simulation model where functions calls to the modal emissions algorithm can be made directly within the native code.

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Table 1
FTP Speed Ranges and Corresponding Speed-Acceleration Products

Cycle Mode Name	Start Speed (mph)	End Speed (mph)	Time in Mode (sec)	Average Speed (mph)	Average Acceleration (mph/sec)	Speed-Acceleration Product (mph^2/sec)
FTP3[a]	5.9	22.5	11	14.2	1.51	21.43
FTP7[a]	6.6	47.5	42	27.05	0.97	26.34
FTP11[a]	4.3	34.9	20	19.6	1.53	29.99
FTP15[a]	5.9	30	13	17.95	1.85	33.28
FTP18[a]	6.6	36	17	21.3	1.73	36.84
FTP22[b]	3.5	25	19	14.25	1.13	16.13
FTP26[b]	6.6	17	8	11.8	1.30	15.34
FTP30[b]	4.5	26	15	15.25	1.43	21.86
FTP35[b]	3.2	28.6	18	15.9	1.41	22.44
FTP37[b]	6.3	28.9	17	17.6	1.33	23.40
FTP40[b]	0	28.5	18	14.25	1.58	22.56
FTP44[b]	4	28	18	16	1.33	21.33
FTP46[b]	0.6	24.9	22	12.75	1.10	14.08
FTP50[b]	5.4	23	9	14.2	1.96	27.77
FTP53[b]	1.5	21.8	20	11.65	1.0	11.82
FTP61[b]	4.8	22	14	13.4	1.23	16.46
FTP66[c]	3	22.4	11	12.7	1.76	22.40
FTP70[c]	3.3	47.5	42	25.4	1.05	26.73
FTP74[c]	1	34.6	20	17.8	1.68	29.90
FTP78[c]	2.6	30.1	13	16.35	2.12	34.59
FTP81[c]	3.3	36.1	17	19.7	1.93	38.01

[a]Cold Transient Mode.
[b]Stabilized Mode.
[c]Hot Transient Mode.

Table 2
Vehicle Mode Percentages Required to Obtain Bag-Specific Emission Rates

	Vehicle Mode Percentages		
	Bag 1	Bag 2	Bag 3
PCCN	100	0	0
PCHC	0	0	100
PCCC	100	0	0
Vehicle Speed (mph)	25.6	16.2	25.05

Note: PCCN = Cold Transient Mode Percentage without a catalyst;
PCHC = Hot Transient Mode Percentage with a catalyst;
PCCC = Cold Transient Mode Percentage with a catalyst.

Table 3
Vehicle Categories

Vehicle Type	**Make, Model, and Year**	**Age of Catalytic Converter (miles)**
Cars (C)	Ford Escort ‘93	50,000
	Ford Taurus LX ‘93	50,000
	Ford Mustang LX ‘93	50,000
	Oldsmobile Cutlass Supreme ‘94	100,000
	Pontiac Grand Prix ‘94	50,000
	Oldsmobile 98 ‘94	50,000
	Cadillac Seville ‘94	100,000
	Oldsmobile Custom Cruiser ‘92	50,000
	Saturn Saturn ‘94	50,000
	Geo Metro ‘93	36,000
	Pontiac Grand Am ‘93	50,000
	Honda Civic ‘92	50,000
	Mitsubishi Mirage ‘93	4,000
	Toyota Camry ‘93	50,000
	Toyota Corolla ‘93	50,000
	Mercedes 420 SEL ‘92	50,000
Light Trucks (LT)	Jeep Cherokee ‘94	50,000
	Ford Ranger 4x2 XLT ‘93	50,000
	Ford F150 4x2 ‘93	50,000
	GMC Sonoma P/U ‘93	100,000
	Chevrolet C10 P/U ‘94	126,000
	Mazda MPV ‘92	90,000
	Nissan Pathfinder ‘92	35,000
Heavy Light Trucks (HLT)	Ford F250 4x2 ‘93	50,000
	Chevrolet Suburban ‘92	30,000
	Chevrolet G30 Van ‘93	30,000
	Chevrolet C30/K30 Duallie ‘94	150,000

Table 4
Modal Multiplier Regression Results

Mode Type	Vehicle Type[a]	Model Type[b]	n[c]	A	b	c	R^2	Root MSE	MSE	p-value
Cold Transient	HLT	Pow	5	$1.55X10^{13}$	-8.571	n/a	0.996	1.867	3.487	0.0001
		Exp	**5**	**271388**	**-0.392**	**n/a**	**0.997**	**1.630**	**2.656**	**7.00E-05**
		Poly	5	0.50315	-32.775	529.929	0.962	7.177	51.506	0.03838
	LT	Pow	5	$1.11X10^{13}$	-8.256	n/a	0.997	3.123	9.753	7.00E-05
		Exp	**5**	**161332**	**-0.339**	**n/a**	**0.998**	**2.681**	**7.186**	**5.00E-05**
		Poly	5	0.88438	-58.235	952.377	0.979	10.019	100.4	0.0215
	C	Pow	5	$4.52X10^{14}$	-9.377	n/a	0.998	2.951	8.707	3.00E-05
		Exp	**5**	**615340**	**-0.388**	**n/a**	**0.999**	**2.846**	**8.102**	**2.00E-05**
		Poly	5	1.22165	-79.779	1292.240	0.967	16.273	264.8	0.03261
Stabilized	HLT	Pow	11	0.1784	0.875	n/a	0.421	0.628	0.395	0.03077
		Exp	**11**	**0.9331**	**0.047**	**n/a**	**0.454**	**0.610**	**0.372**	**0.02298**
		Poly	11	0.007789	-0.198	3.124	0.473	0.636	0.404	0.077
	LT	Pow	11	0.4085	0.832	n/a	0.688	0.687	0.472	0.00159
		Exp	**11**	**1.949**	**0.045**	**n/a**	**0.759**	**0.605**	**0.366**	**0.00048**
		Poly	11	0.01876	-0.529	7.601	0.825	0.545	0.297	0.00093
	C	Pow	11	0.3038	0.782	n/a	0.516	0.594	0.353	0.01273
		Exp	**11**	**1.3001**	**0.043**	**n/a**	**0.582**	**0.552**	**0.305**	**0.00634**
		Poly	11	0.0135	-0.404	5.542	0.665	0.524	0.275	0.01264
Hot Transient	HLT	**Pow**	**5**	**23336412**	**-4.886**	**n/a**	**0.885**	**0.835**	**0.698**	**0.01714**
		Exp	5	456.2	-0.194	n/a	0.855	0.937	0.879	0.02447
		Poly	5	0.04636	-3.065	51.237	0.938	0.751	0.565	0.06201
	LT	Pow	5	488.98	-1.635	n/a	0.323	1.237	1.530	0.31772
		Exp	**5**	**11.73**	**-0.060**	**n/a**	**0.347**	**1.215**	**1.475**	**0.29602**
		Poly	5	-0.001006	-0.066	4.938	0.365	1.467	2.151	0.63473
	C	**Pow**	**5**	**6758**	**-2.332**	**n/a**	**0.843**	**0.634**	**0.402**	**0.02777**
		Exp	5	29.54	-0.082	n/a	0.795	0.725	0.526	0.04221
		Poly	5	0.02697	-1.814	32.112	0.956	0.411	0.169	0.0439

[a]"HLT"=Heavy Light Truck; "LT"=Light Truck; "C"=Car.
[b]"Pow"=power series; "Exp"=Exponential; "Poly"=Polynomial.

[c]Number of data points used in regression.
Note: Selections in bold are considered best choices for modeling according to goodness of fit criteria.

	Mode 1	Mode 2	Mode 3	Mode j
Vehicle 1	E11	E12	E13	E1j
Vehicle 2	E21	E22	E23	E2j
Vehicle 3	E31	E32	E33	E3j
Vehicle k	Ek1	Ek2	Ek3	Ekj

↓

M11=E11/E1	M12=E12/E1	M13=E13/E1	M1j=E1j/E1
M21=E21/E2	M22=E22/E2	M23=E23/E2	M2j=E2j/E2
M31=E31/E3	M32=E32/E3	M33=E33/E3	M3j=E3j/E3
Mk1=Ek1/Ek	Mk2=Ek2/Ek	Mk3=Ek3/Ek	Mkj=Ekj/Ek

↓

M1=(M11+M21+M31+ ... +Mk1)/k
M2=(M12+M22+M32+ ... +Mk2)/k
M3=(M13+M23+M33+ ... +Mk3)/k

Mj=(M1j+M2j+M3j+ ... +Mkj)/k

Ekj = emission factor for a mode (e.g. accel., decel., etc.) that corresponds to a speed range
Ek = overall bag emission factor for a specific vehicle
Mkj = modal multiplier based on vehicle and mode
Mj = average modal multiplier for a mode

Figure 1

Methodology for Derivation of Modal Multipliers

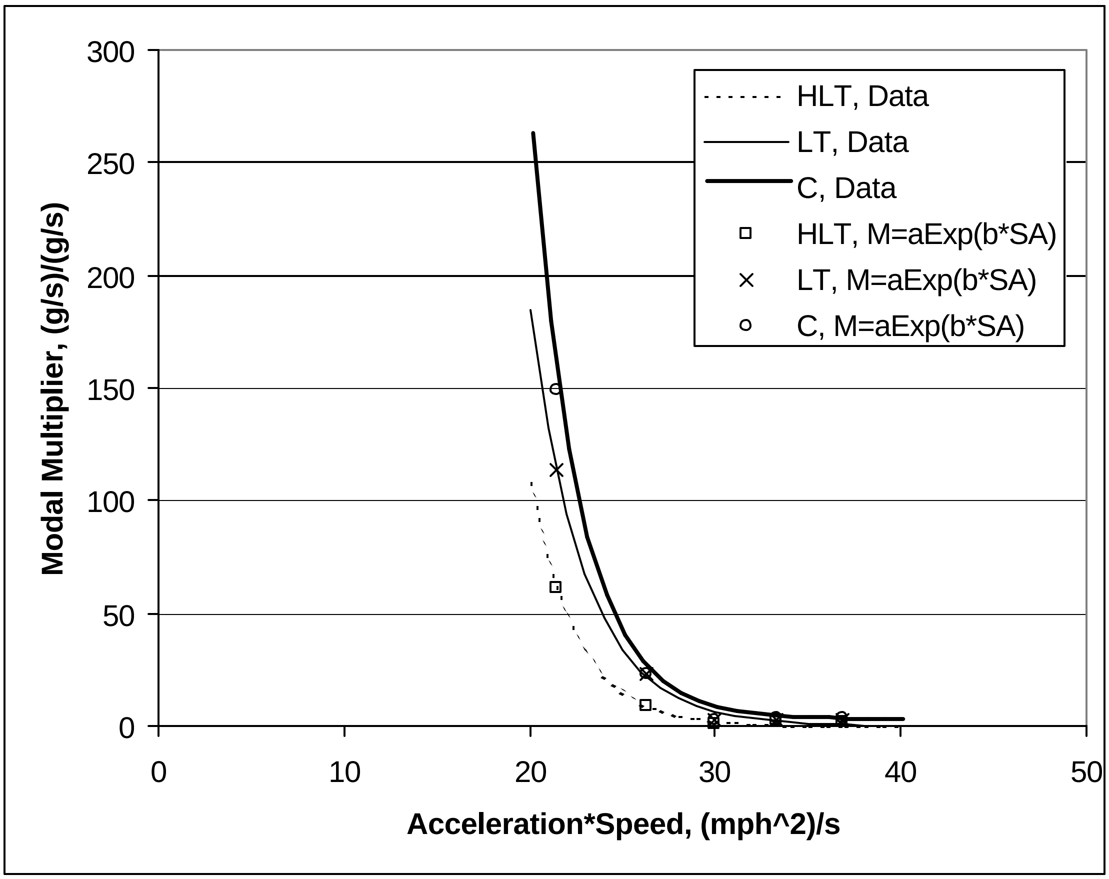

Figure 2
Regression Analysis for the Cold Transient Mode

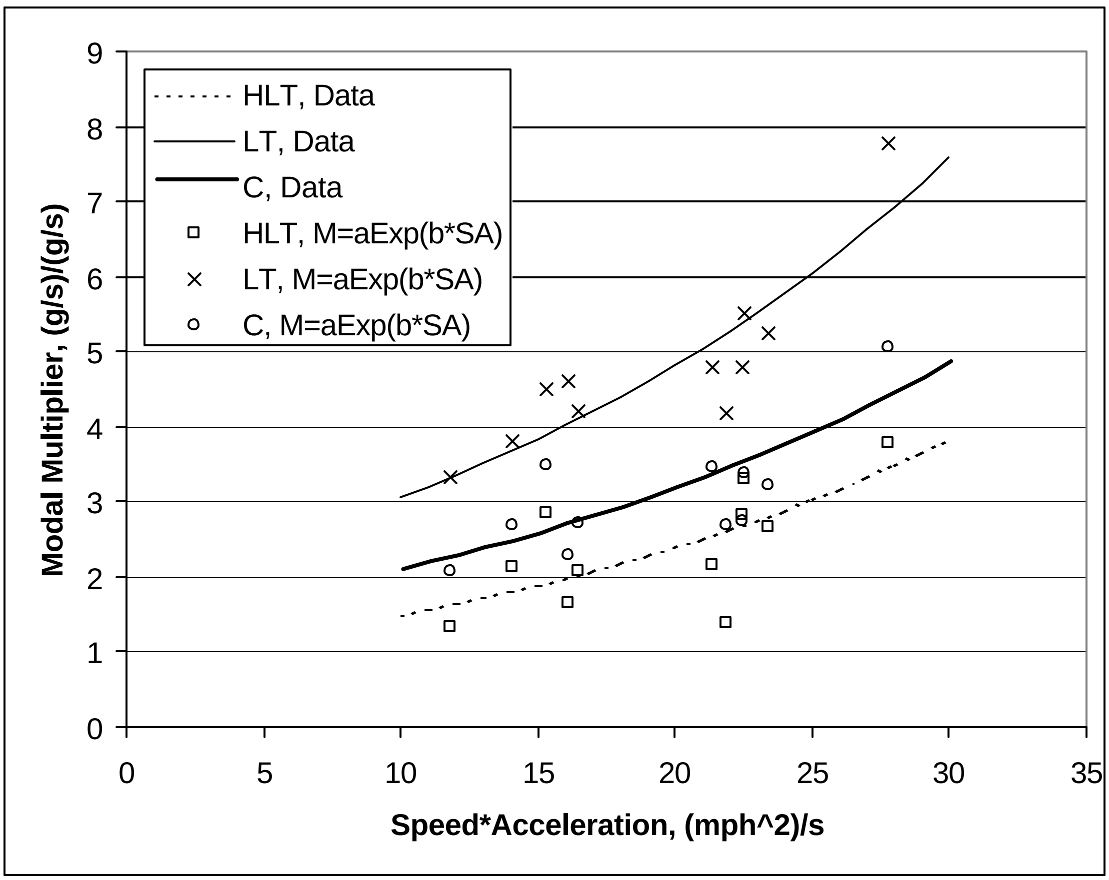

Figure 3
Regression Analysis for the Stabilized Mode

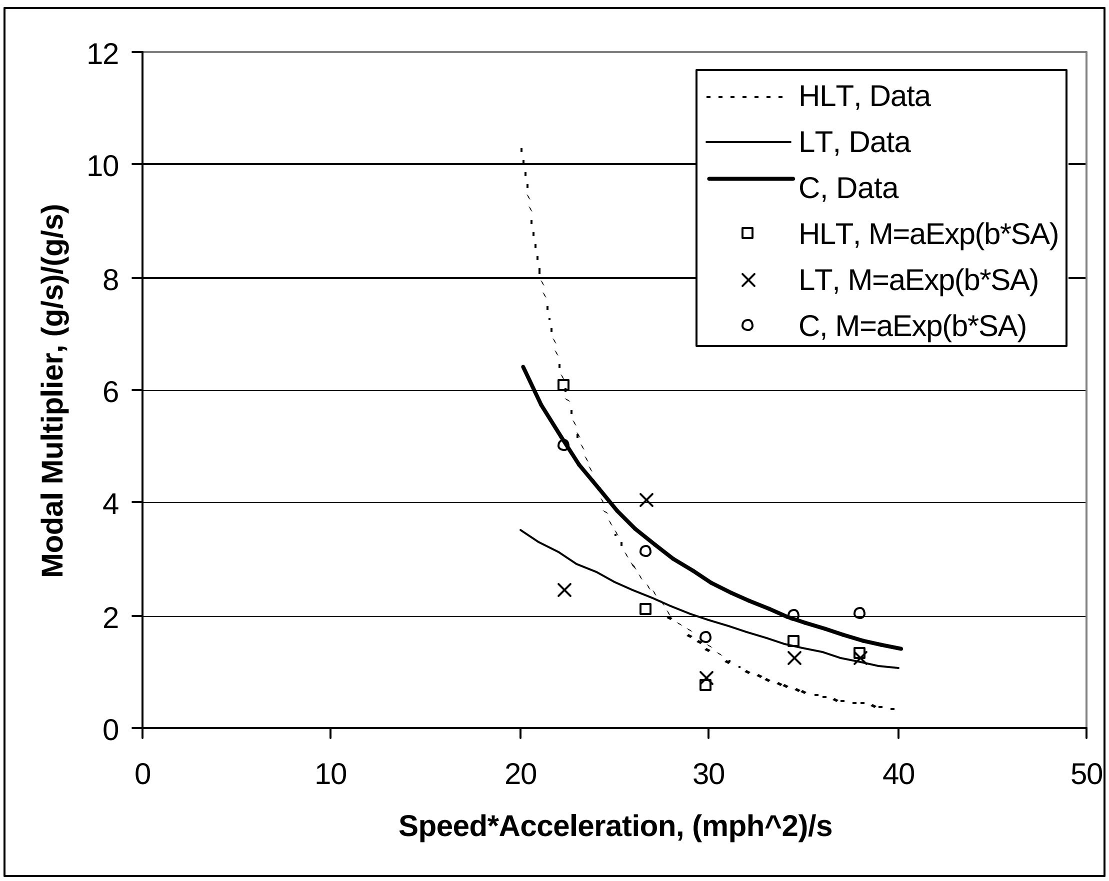

Figure 4
Regression Analysis for the Hot Transient Mode

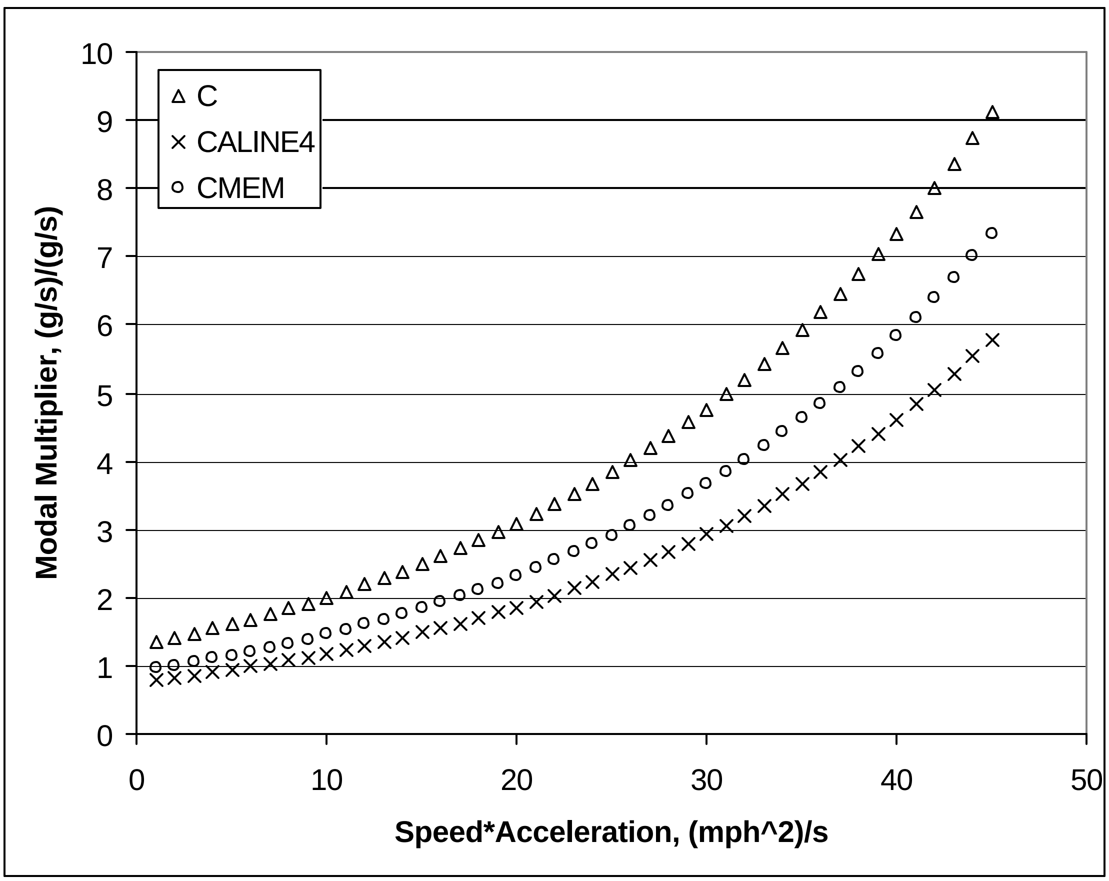

Figure 5
Comparisons of Modal Multipliers Obtained from Different Models