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Determination of Start Emissions as a Function of Mileage and Soak Time for 1981-1993 Model Year Light-Duty Vehicles

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1.0 INTRODUCTION

MOBILE6 will allocate vehicle exhaust emissions to either the "extra" emissions associated with engine start (start emissions) or the "base" emissions associated with travel (running emissions). This distinction is to some extent an artificial constraint since in reality "start" emissions in part will be released while the vehicle is in motion. However, it is a useful constraint and not too far from physical reality, in at least warm weather driving conditions, when the extra emissions from a start end after only 1 or 2 minutes of driving. This split allows the separate characterization of start and running emissions for correction factors such as fuel effects and ambient temperature. It also allows a more precise weighting of these two aspects of exhaust emissions for particular situations such as morning commute, parking lots and freeways. This document describes the methodology used to calculate start emissions as a function of mileage and soak time for use in MOBILE6. The results for model year 1981-1993 light-duty cars and light-duty trucks are presented. The deterioration of running emissions are addressed in a separate document (EPA Report Number M6.EXH.001).

This document is organized into six sections. The first section is the short introductory section. Section 2 describes the FTP data sources and the model year and technology groups which are used. Section 3 provides a definition of start emissions in mathematical terms and shows the relationship between start emissions and the Federal Test Procedure (FTP) emissions. This includes a description of the FTP cycle, the Hot505 cycle, and a definition of cold start and hot start emissions. Section 4 describes the methodology used to predict start emissions as a function of soak time. Section 5 shows the algorithm used to predict start emissions versus mileage. Section 6 contains an example of the final start emission results as used in MOBILE6 as a function of both deterioration and soak time. Appendix A briefly discusses the methodology and rational for using a high emitter correction factor and presents the fleetwide high emitter penetration fractions.

2.0 DATA SOURCES USED

The basic datasets used to determine in-use deterioration are based on FTP testing. (I/M data from Dayton, Ohio were also used to correct the results for recruitment bias which EPA believes affects the FTP test samples - see Appendix A). Three FTP data sources were used: 1) the test results from the EPA laboratory in Ann Arbor, Michigan, 2) the data received from AAMA (American Automobile Manufacturers Association) based on testing conducted in Michigan and Arizona, and 3) the API (American Petroleum Institute) data collected in Arizona. The model years in the dataset range from 1981 through 1993, and contain both cars and trucks. Table 1 gives a breakdown by vehicle type, model year, and technology for the three datasets combined.

Table 1
Distribution of Vehicles by Model Year and Technology*

MYR	Cars OPLP	Cars CL Carb	Cars TBI	Cars PFI	Cars ALL	MYR	Trucks OPLP	Trucks CL Carb	Trucks TBI	Trucks PFI	Trucks ALL
81	367	657	15	29	1068	81	124				124
82	71	71	74	8	224	82	45				45
83	63	57	127	62	309	83	8	3			11
84	5	30	46	35	116	84	26	22		1	49
85	24	74	56	66	220	85	33	30	13	6	82
86	7	34	60	92	193	86	14	9	23	41	87
87	1	17	76	106	200	87			6	4	10
88		15	69	113	197	88					0
89		22	38	103	163	89					0
90			160	250	410	90			144	1	145
91			91	426	517	91			141	144	285
92			57	347	404	92			92	92	184
93			29	366	395	93			90	93	183
ALL	538	977	898	2003	4416	ALL	250	64	509	382	1205

* No entry indicates no data available for that model year/technology type in the FTP dataset used for this analysis.

In general, most of the 1990+ model year vehicle data were supplied by AAMA, and most of the pre-1990 data were supplied by the EPA laboratory testing. The API sample is a relatively small sample (99 cars and trucks). Its chief appeal is that the vehicles all have generally higher mileage readings than the rest of the sample (all over 100,000 miles). The other general trend in the data is toward PFI technology, and away from the others. This is seen in the 1990+ vehicles which are predominately PFI with some TBI still present. The 1981 - 1989 model years start with a high percentage of carbureted and some open loop, but end with mostly TBI and PFI technology. Although not explicitly shown in the tables, new catalyst technology was phased slowly into the fleet starting in the mid 1980's.

For analysis, the cars and trucks were placed into the model year/technology groups shown below. Trucks were separated into five different groups by pollutant due to differences in certification standards.

CARS MY Group / Technology Type	**TRUCKS** MY Groups / Technology Type
HC/CO/NOX	HC/CO/NOX
1988-93 PFI	1988-93 PFI
1988-93 TBI	1988-93 TBI
1983-87 FI	1981-87 FI
1986-93 Carb	1984-93 Carb
1983-85 Carb	1981-83 Carb
1981-82 FI	
1981-82 Carb	

The technology groups are closed-loop ported fuel injection (PFI), closed-loop throttle body injection (TBI), and carbureted (CARB). FI refers to a combination of PFI and TBI. CARB includes both closed-loop and open-loop vehicles which are carbureted. These model year/technology grouping boundaries were selected on the basis of changes in emission standards or the development/refinement of new fuel metering or catalyst technologies. It is assumed that as of 1990, carbureted technology had a very tiny market share, and are included with the previous carbureted group. Because of the relatively large amount of 1988-93 fuel injected data, the category was split into PFI technology and TBI technology for both cars and trucks. This produces separate deterioration functions based on this fuel delivery technology and allows the modeling of the future penetration of PFI technology into the in-use fleet.

3.0 DEFINITION OF START EMISSIONS

3.1 Overview of the Federal Test Procedure (FTP)

The Federal Test Procedure (FTP) is a test cycle which is used to certify new vehicles to emission performance standards (see 40 CFR Part 86, Subpart B, Section 86.144). The FTP consists of a cold start segment (Bag 1), a hot stabilized segment (Bag 2), and a hot start segment (Bag 3). Initially, the vehicle is stored for a minimum of 12 hours before testing to simulate a 12 hour overnight soak period. The vehicle is then driven over the cold start segment, which lasts 505 seconds over a length of 3.59 miles, and the emissions collected as Bag 1. The latter part of the driving in Bag 1 occurs with the engine and catalyst in a hot stabilized condition. Bag 2 emissions are then immediately collected from the hot stabilized segment, which lasts 867 seconds over a length of 3.91 miles. After a 10 minute soak, the 505 seconds of the start segment is then repeated and the emissions collected as Bag 3.

The FTP composite emission rate is a weighted combination of the three measured bags to represent two trips. The first trip is a cold start trip after a 12 hour soak, and the other is a hot start trip after a 10 minute soak. Each trip is a “LA4" cycle, which is a combination of the 505 cycle (either Bag 1 or Bag 3) and the Bag 2 cycle. In a typical FTP test, the Bag 2 is only measured once and the results are used for both trips. Since the 505 cycle is 3.59 miles long and the Bag 2 cycle is 3.91 miles long, each LA4 trip is 7.5 miles long. The cold start trip is weighted at 43% and the hot start trip weighted 57%. If the cold start trip is 43% of the driving, then the vehicle miles traveled (VMT) in Bag 1 (containing the cold start) is:

FTP Bag 1 VMT Weighting = 43% * (3.59 miles / 7.5 miles) = 0.206

The hot start trip is 57% of driving, and the VMT weighting for Bag 3 (containing the hot start) is:

FTP Bag 3 VMT Weighting = 57% * (3.59 miles / 7.5 miles) = 0.273

The remaining VMT is from stabilized driving, represented by Bag 2. Since Bag 2 is used for both the cold start and hot start trips, it uses VMT weighting from both.

FTP Bag 2 VMT Weighting = (43% + 57%) * (3.91 miles / 7.5 miles) = 0.521

The standard VMT weighting of the bags reported in grams per mile for the full FTP are:

FTP = (Bag 1 * 0.206) + (Bag 2 * 0.521) + (Bag 3 * 0.273)

where the fractions represent the amount of vehicle miles traveled within the three modes during the FTP trip, and Bag1, Bag2, Bag3 and the FTP emissions are in grams per mile (g/mi).

3.2 Overview of the Hot Running 505 and Its Use

The FTP testing method outlined above does not allow the precise separation of start and running emissions, since Bags 1 and 3 contain both start and running emissions. Bag 2 of the FTP does not contain an engine start; however, the driving cycle used in the second bag is significantly different from the cycle used for Bags 1 and 3. Thus, to estimate the amount of FTP emissions that can be allocated to engine start, the concept of the Hot Running 505 (HR505) is needed.

The HR505 is an extra 505 cycle performed immediately following bag 3 of the FTP. It uses an identical driving cycle as the first and third bags of the FTP, but does not include an engine start. For more information, refer to the document "The Determination of Hot Running Emissions from FTP Bag Emissions", report number M6.STE.002. With a HR505 emission result, it is possible to compare the results obtained from the HR505 to the results from Bags 1 and 3 of the FTP to determine the portions of Bags 1 and 3 attributable to start emissions following a 12 hour soak and start emissions following a 10 minute soak, respectively.

Since the HR505 has not historically been included in FTP test programs, a method of estimating the HR505 was developed, as described in report M6.STE.002. Briefly, HR505 emissions were measured from a sample of 77 vehicles tested under EPA contract. The results from this vehicle sample were used to develop a correlation between the HR505 and FTP bag data. This correlation was then used to estimate HR505 results for the FTP dataset used for this analysis.

3.3 Basic Start Emission Rate

For MOBILE6, the basic unit of engine start emissions is defined as a start after a 12 hour soak. The units for engine start emissions will be grams, instead of grams per mile, since start emissions will not be allocated by vehicle miles traveled. The engine start basic emission rate can be determined by subtracting the HR505 emission rate from the Bag 1 emission rate (in grams per mile) using the nominal distance traveled in the 505 driving cycle:

Basic Start Emission Rate (grams) = [Bag 1(g/mi) - HR505(g/mi)] * 3.59 miles

For illustration purposes, the average basic start emission rates (in grams) after a 12 hour soak were calculated for each model year and are shown in Tables 2 and 3 for cars and trucks.

Start emissions after a 10 minute soak can also be estimated from the Bag 3 and HR505 emission rates, analogous to the basic start emission rate:

Start Emissions after 10 minute soak (grams) = [Bag 3(g/mi) - HR505(g/mi)] * 3.59 miles

The average start emissions after a 10 minute soak are also shown in Tables 2 and 3 for each model year and for cars and trucks.

For some FTP tests of some cars, the predicted HR505 emissions are higher than Bag1 and/or Bag3 emissions. This causes the start emissions to be negative. This probably is due to intermittent emission control system defects. Except in some cases of very small samples, the negative values were retained in the analysis. Sample sizes are shown in Table 1.

4.0 Basic Start Deterioration with Mileage

4.1 Definition of Categories

The basic modeling concept behind the start emission factor methodology is that the fleet can be represented as two types of vehicle emitter categories. These two types are termed “high” emitters, and “normal” emitters. The “high” emitters have FTP average emission levels which are considerably higher than the overall mean emission levels, and significantly higher than their FTP standards, indicating that they have problems with their emission control systems. The “normal” emitters are low and average emitting vehicles with emission control systems which are generally functioning properly. The overall fleet emission factor is a weighted average of the high and normal emitters.

The high/normal emitter modeling concept is also used in the estimation of running emissions, and is discussed in depth in other reports. For both start and running emissions, the high/normal concept allows for corrections due to recruitment bias against higher emitting vehicles, and for more accurate estimates of the effects of I/M programs, fuel effects, temperatures, etc.

In the data analysis, vehicles were defined as normal emitters for a specific pollutant if their FTP HC emissions were less than twice the applicable new car certification standard, or their FTP CO emissions were less than three times the applicable new car

Table 2
Mean Estimated Start and FTP Emission Levels by Model Year for Light-Duty Cars in the FTP Dataset

Basic start (after 12 hour soak) grams				Start (after 10 min soak) grams				Composite FTP grams/mile			
MYR	**HC**	**CO**	**NOx**	**MYR**	**HC**	**CO**	**NOx**	**MYR**	**HC**	**CO**	**NOx**
81	4.002	46.419	1.373	81	0.610	5.115	0.041	81	0.706	9.667	0.897
82	2.445	36.378	1.237	82	0.373	4.843	-0.045	82	0.789	8.318	0.872
83	2.399	26.112	1.264	83	0.400	3.827	0.150	83	0.431	5.073	0.806
84	2.950	34.827	1.190	84	0.513	3.418	0.047	84	0.756	9.968	0.893
85	3.468	30.353	1.204	85	0.506	4.737	0.095	85	0.533	6.935	0.770
86	2.526	26.639	1.432	86	0.298	2.082	0.241	86	0.926	10.43	0.713
87	2.712	20.030	1.376	87	0.597	2.104	0.170	87	0.656	8.366	0.790
88	2.831	19.716	1.419	88	0.406	1.147	0.223	88	0.406	4.574	0.668
89	2.254	18.610	1.434	89	0.379	2.524	0.216	89	0.311	3.911	0.652
90	2.169	18.677	1.930	90	0.332	2.219	0.611	90	0.274	3.614	0.633
91	2.183	19.494	1.443	91	0.275	2.132	0.530	91	0.237	3.145	0.525
92	2.271	18.878	1.645	92	0.304	2.595	0.485	92	0.267	4.328	0.508
93	2.312	21.030	1.801	93	0.310	2.564	0.392	93	0.225	2.551	0.466

Table 3
Mean Estimated Start and FTP Emission Levels by Model Year for Light-DutyTrucks in the FTP Dataset

Basic start (after 12 hour soak) grams				Start (after 10 min soak) grams				Composite FTP grams/mile			
MYR	**HC**	**CO**	**NOx**	**MYR**	**HC**	**CO**	**NOx**	**MYR**	**HC**	**CO**	**NOx**
81	7.342	107.501	1.055	81	1.212	14.211	0.385	81	1.275	18.158	1.752
82	7.909	116.584	-0.119	82	1.489	14.189	0.006	82	1.732	16.774	1.732
83	6.537	104.817	0.796	83	1.577	18.657	-0.209	83	1.361	13.226	1.436
84	5.219	95.893	0.299	84	1.098	20.057	0.004	84	0.802	10.633	1.405
85	4.766	84.621	0.457	85	0.854	7.742	0.102	85	1.281	14.465	1.388
86	3.752	41.196	0.729	86	0.607	2.148	0.128	86	0.823	8.789	1.057
87	3.352	26.635	1.266	87	0.566	1.433	0.017	87	0.401	4.610	0.605
88				88				88			
89				89				89			
90	4.705	45.331	4.683	90	0.930	7.037	0.765	90	0.800	9.510	0.885
91	3.521	41.128	2.761	91	0.878	7.129	0.519	91			
92	3.656	41.446	3.054	92	0.654	5.746	0.656	92			
93	3.644	40.557	2.736	93	0.589	4.634	0.676	93	0.420	5.363	0.847

certification standard, or their FTP NOx emissions were less than twice the new car certification standard.

Vehicles were defined as high emitters for a specific pollutant if their FTP HC emissions or FTP CO emissions exceeded twice or three times the applicable new car certification standard, respectively, or their FTP NOx emissions were two times the new car certification standard. Because high NOx emissions often occur with low HC and/or low CO emissions, and sometimes even HC can be high and CO normal, the three categories were kept separate. Thus, a vehicle could be a high HC emitter, but a normal CO and NOx emitter.

4.2 Calculation of Start Emission Rates for Normal Emitters

Emission rates for normal emitters were calculated by least squares regression of the emissions of the normal emitters versus mileage. The regression was done for each pollutant / model year / technology group. The start emission regression coefficients for cars are shown in Table 4a and for trucks in Table 4b. The column labeled ZML contains the zero mile coefficients, and the column DET contains the deterioration coefficients (slope) from the regressions. Appendix B Tables B-3 through B-8 show the regression statistics for normal emitter cars and trucks for each pollutant.

Table 4a
Regression Coefficients for START Emissions from Normal Emitter CARS

MY Group	Tech Group	HC Coefficients		CO Coefficients		NOx Coefficients	
		ZML	DET	ZML	DET	ZML	DET
1988-93	PFI	1.9987	0.006830	18.972	0.00703	1.444	0.00220
1988-93	TBI	1.9019	0.002679	19.233	0.00000	2.300	0.00000
1983-87	FI	2.3589	0.001388	19.949	0.00000	1.461	0.00141
1986-89	Carb	1.4934	0.018238	24.698	0.10947	1.405	0.00000
1983-85	Carb	1.5892	0.009408	24.442	0.10577	0.748	0.00524
1981-82	FI	2.3543	0.008533	20.038	0.22673	1.530	0.00059
1981-82	Carb	2.1213	0.013610	28.637	0.22673	1.601	0.00000

Table 4b
Regression Coefficients for START Emissions from Normal Emitter Light Trucks

MY Group	Tech Group	HC Coefficients		CO Coefficients		NOx Coefficients	
		ZML	DET	ZML	DET	ZML	DET
1988-93	PFI	2.873	0.00000	32.178	0.0168	1.597	0.00000
1988-93	TBI	4.073	0.01309	42.456	0.1411	4.294	0.00324
1981-87	FI	2.599	0.00964	23.497	0.0613	1.384	0.00000
1984-93	Carb	3.916	0.00854	78.286	0.2564	0.143	0.00436
1981-83	Carb	6.817	0.00154	98.432	0.3240	1.082	0.00000

4.3 Calculation of Start Emission Rates for High Emitters

High emitters are the vehicles in the fleet which likely have problems with their emission control systems, as evidenced by emission levels which are considerably higher than the FTP standards. In the analysis they were defined as those vehicles exceeding either twice FTP standards for HC or NOX or three times FTP standards for CO. The emissions line is a flat horizontal line because the emissions of a high emitter were not a statistically significant function of mileage. In addition, the relatively small sample sizes of high emitters make regression determined mileage coefficients unreliable indicators of actual behavior. Table 5a shows the average emissions of the high emitters (cars only) for the pollutant / model year / tech groups, and Table 5b shows the analogous results for light trucks. Appendix B Tables B-1 and B-2 show the sample size and standard deviation statistics for the High emitter cars and trucks. It should be noted by the reader that the data were combined across model year and technology group in some cases to produce a larger sample of high emitters.

For NOX start emissions, the normals and the highs were combined together, and the emissions were regressed versus mileage. This has the effect of eliminating the NOX high emitter group for start emissions. This combination was done for two reasons. First, for many of the model year / tech groups the average NOX start emissions of high emitters were found to not be statistically significantly different from start emissions from the normals. This was found to be the case even when different definitions of a high emitter were tried (1X FTP NOX, 1.5X FTP NOX, and 2X FTP NOX). This phenomenon is consistent with the mechanisms of NOX formation - higher emissions under lean high temperature / load FTP conditions, and lower during rich and cooler start conditions. Second, the sample sizes for NOX high emitters were smaller in both an absolute sense, and in comparison to the HC and CO high emitter sample.

Table 5a
Mean START Emissions of High Emitter CARS

MY Group	Tech Group	HC Mean	CO Mean	NOx Mean
1988-93	PFI	4.829	38.06	Same as Normals
1988-93	TBI	4.829	38.06	Same as Normals
1983-87	FI	5.313	65.31	Same as Normals
1986-89	Carb	10.520	92.82	Same as Normals
1983-85	Carb	10.520	92.82	Same as Normals
1981-82	FI	5.313	92.82	Same as Normals
1981-82	Carb	10.520	92.82	Same as Normals

Table 5b
Mean START Emissions of High Emitter Trucks

MY Group	Tech Group	HC Mean	CO Mean	NOx Mean
1988-93	PFI	5.212	83.862	Same as Normals
1988-93	TBI	5.212	83.862	Same as Normals
1981-87	FI	5.826	60.319	Same as Normals
1984-93	Carb	9.406	162.115	Same as Normals
1981-83	Carb	17.865	179.549	Same as Normals

The other anomally in the results was the HC and CO high emitter emission levels for the 1990-93 TBI group. In both of these cases the average start emission levels of the few cars tested were judged to be unrealistically low. For the case of CO, the value was -123.84 grams, and for HC it was 0.0356 grams. These low average levels are the result of small sample size, and the possibility of negative values when the hot running 505 on a particular car is greater than Bag1 of the FTP. Rather than insert negative values in the MOBILE6 model, the HC and CO high emitter emission levels from the 1988-93 PFI group were substituted in the 1988-93 TBI group. This is a reasonable assumption since these vehicles are generally about the same age and model year vintage, and have reasonably similar emission control technology.

4.4 Fraction of High and Normal Emitters in the Fleet

The basic start emission factor is computed from a weighted average of the highs and normals, and the fraction of high emitters in the fleet is the weighting factor for the highs and normals. The fraction of high emitters in the fleet and the definition of a high emitter are based on FTP emission results. Since similar definitions of a high emitter were not available in running and start units, the consistent FTP high emitter definition and high emitter fraction values were used for both start and running, but only for HC an CO emissions. For NOx emissions, the high emitter fraction for running emissions is the same as the FTP fraction, but the start fraction is not. The start NOx high fraction is assumed to be zero because NOx emissions rarely occur in high concentration during start operation. A quick analysis of the data using various definitions of a high emitter for start and running indicated that this was a reasonable choice. However, from a vehicle engineering perspective, start emission problems sometimes are not well associated with running operation emission problems (i.e., choke system malfunctions).

Appendix A presents the fraction of HC and CO high emitters in the fleet at selected mileages / ages for each pollutant (see document M6.IM.001 for further details). The fraction of NOX high emitters is not shown because for NOX because the Normals and Highs are assumed to have the same emission rate (no start NOX highs are assumed to exist). Appendix A also provides a brief discussion of the high emitter adjustment factor used to correct for recruitment bias inherent in FTP data type sampling. This adjustment factor generally increased the rate of high emitters in the fleet over the fraction that would be predicted based on the FTP sampling.

4.5 Calculation of Basic Start Emission Rates

The basic start emission rate is calculated for each combination of vehicle type / pollutant / model year group / technology group. The units are start emissions in grams. Equation 1 is used to calculate the basic (mean) start emission rate from the high and normal emitter emission values and the rate of high emitters in the fleet. For NOX emissions a special case of this equation is used where the normal and high emission rates are set equal to each other.

START = ST_High_ave * Highs + ST_Norm_ave * Normals Eqn 1

Where:

Highs = fraction of High emitters
Normals = fraction of Normal emitters
START is the basic (mean) emission rate
ST_High_ave is the high emitter start emission average
ST_Norm_ave is the normal emitter start emission average

Where:

Highs + Normals = 1 Eqn 2

5.0 Start Emissions Versus Soak Time

Start emissions will now be modeled as a function of soak time in MOBILE6. As such, the model will be able to account for the entire distribution of soak times observed in the fleet rather than just two soak time points (10 and 720 minutes) that were implicit in the FTP test procedure and in MOBILE5. The model will allow the soak time to range from a minimum of zero minutes up to a 12 hour soak period (720 minutes). Soak periods exceeding 12 hours will be assumed to be the same as for a 12 hour soak.

The MOBILE6 relationship between start emissions and soak time was developed by using the FTP database, and a California soak time and engine start model (CARB model). The FTP start emission data were available only at the soak time periods of 10 minutes (hot start), and 720 minutes (cold start). The CARB model predicted start soak emission effects for the entire range of soak time lengths (0 to 720 minutes). The details of CARB model are documented in the report “Methodology for Calculating and Redefining Cold and Hot Start Emissions”.

The start emissions model developed for MOBILE6 is really just an adjusted or calibrated version of the CARB model. It uses the FTP start emission data from the two FTP soak times to adjust the CARB model curves at the ten minute level. This has the effect of forcing the CARB model curves through these two points, but retaining the general shape of the CARB model curve. The start emission data points at 10 minutes and 720 minutes are derived from the FTP dataset described earlier. The California interpolation curves (California Soak Function) is a function of pollutant and catalyst type.

Basic Start Soak Equation

The general form of the MOBILE6 start emissions as a function of soak time calculation is shown in Equation 3.

Start Emissions (@ soak time) = Basic Start Emissions (@ 12 hour soak) *
Soak Function(@soak time) Eqn 3

At a given soak time, it is the product of the basic 12 hour cold start emission factor and the soak function. The Basic Start Emissions are the start emission factors discussed previously in this document. The Soak Function is a multiplicative correction factor that converts the basic 12 hour start emission factor into a cold start emission factor at any soak time length. Mathematically, the Soak Function is defined in Equation 4.

Soak Function = California Soak Function * [Ratio+(1-Ratio)*((SoakTime-10)/(X-10))] Eqn 4

The terms used in the equation re defined below.

California Soak Function:

The California Soak Function is the basis of the MOBILE6 start soak time model. It is an empirical relationship derived by the California Air Resources Board (CARB), and used in the EMFAC model to calculate start emissions as a function of soak time. Upon review of the CARB document "Methodology for Calculating and Redefining Cold and Hot Start Emissions", EPA found it to be the only available empirical model for this purpose.

Mathematically, the California Soak Function has the following general form:

California Soak Function = a + b*soak length + c*soak length ^ 2 Eqn 5

where soak length is the time in minutes since the last engine operation, and a, b, and c are soak function coefficients. These are shown in Table 6 for each pollutant, three different catalyst types (the coefficients for catalyst-equipped vehicles are for the model year/technology groups examined in this report), and by soak time domain. The soak time domain is divided into two groups (a low domain and a high domain) which are listed in Table 6.

Table 6
Coefficients for Adjusting Engine Start Emissions for Soak Time

(from “Methodology for Calculating and Redefining Cold and Hot Start Emissions”, CARB)

Non-Catalyst Vehicles						
	HC Curve 1	HC Curve 2	CO Curve 1	CO Curve 2	NOX Curve 1	NOX Curve 2
Constant	0.38067	0.43628	0.43803	-0.08541	1.31568	2.48061
minutes	-0.00163	0.00078	-0.00998	0.00303	0.02752	-0.00018
$minutes^2$	6.64E-05	0	7.01E-05	-2.11E-06	-0.00015	-2.6E-06
domain(min)	0-52	53-720	0-119	120-720	0-119	120-720
Catalyst Equipped Vehicles						
	HC Curve 1	HC Curve 2	CO Curve 1	CO Curve 2	Nox Curve 1	NOx Curve 2
Constant	0	0.57130	0	0.70641	0.11796	1.12983
minutes	0.01272	0.00072	0.01195	0.00033	0.02967	2.21E-05
$minutes^2$	-6.30E-05	-1.76E-07	-4.76E-05	1.00E-07	-0.00021	-3.04E-07
domain(min)	0-89	90-720	0-116	117-720	0-61	62-720
Electrically Heated Catalyst Equipped Vehicles						
	HC Curve 1	HC Curve 2	CO Curve 1	CO Curve 2	Nox Curve 1	NOx Curve 2
Constant (a)	0	0.50641	0	0.44733	1.05017	1.37178
minutes (b)	0.00561	0.00069	0.00707	0.00162	0.00362	0.00027
$minutes^2$ (c)	-5.09E-06	0	-1.33E-05	-1.18E-06	-5.57E-06	-1.09E-06
domain(min)	0-117	118-720	0-107	108-720	0-113	114-720

California Soak Function = a + b * minutes + c * $minutes^2$ (where minutes is time since last engine operation (i.e., soak time))
The Soak Function is the grams per soak time i divided by the grams per overnight soak (720 minutes or 12 hours)

Ratio

The Ratio is the variable shown in Equation 4. It is a ratio of two ratios, and is shown mathematically in Equation 6.

$$\text{Ratio} = \frac{\dfrac{\text{EPA Start Emissions at 10 minutes}}{\text{EPA Start Emissions at 720 minutes}}}{\dfrac{\text{CARB Start Emissions at 10 minutes}}{\text{CARB Start Emissions at 720 minutes}}} \qquad \text{Eqn 6}$$

or

Ratio = EPA Ratio / CARB Ratio

The EPA ratio for each pollutant was derived empirically from FTP hot and cold start test data by calculating a hot start emission factor and a cold start emission factor using the equations in Section 3.3, and dividing the Start @10 minutes (hot start) by the Start @ 720 minutes (cold start). One value for each pollutant was developed that included all technologies and vehicle types. These values, used in the numerator of the equation, are:

EPA Ratio	HC	=	0.160
EPA Ratio	CO	=	0.112
EPA Ratio	NOx	=	0.204.

The statistics from the data analysis used to generate these ratios is provided in the attached document STAT.lst.

The CARB ratios were computed by inserting a soak time of 10 minutes and a soak time of 720 minute into Equation 5 for catalyst equipped vehicles. For catalyst equipped vehicles, the ratios were for each pollutant.

CARB Ratio	HC	=	0.1209
CARB Ratio	CO	=	0.1147
CARB Ratio	NOx	=	0.3937

Differences in these ratios reflect differences in the hot and cold start data from EPA and California. Note there are only small differences between the EPA and CARB results for CO start emissions.

The final ratios used in Equation 4 is the ratio of the EPA and CARB ratios. These are shown below for each pollutant.

Ratio HC	=	1.3234
Ratio CO	=	0.9765
Ratio NOx	=	0.5182

SoakTime

The soak time is the time duration between successive engine starts in minutes. It can range from zero minutes to 720 minutes.

X term: This term is defined to be zero for soak times from 0-10 minutes. For the range from 10 minutes to 720 minutes, it is set equal to the highest minute in the domain of the California Soak Function. For example, HC emissions from catalyst equipped vehicles have two time domains in Table 6. These are 0-89 minutes and 90-720 minutes. Thus, for this example, X = 0 for times of 10 minutes or less, and X = 89 for times from 11 minutes through 89 minutes. No soak adjustment is applied for the remaining soak period of 90 minutes through 720 minutes. Only the California Soak Function is used.

6.0 START EMISSION RESULTS

Start emissions are both a function of vehicle deterioration represented by mileage, and soak time. In previous sections the results were shown separately. In this section, examples of the results are shown with both effects combined.

Shown in the linked EXCEL spreadsheets (CAR_BER.xls and TR_BER.xls) is a sample calculation of the basic emission start factors for the various model year groups and pollutants. It includes calculations for both start and running emissions. The calculations in the spreadsheet use Equation 1 in this document, and show the magnitude of the start emission factors that will be used in MOBILE6.

The statistical results and output are too voluminous to present directly in this document. However, they are available in the linked document (stat.lst). The statistical software SPSS was used to perform the linear regressions and compute the means. In general, the regression correlation coefficients (r-squared) are not high (< 0.10), and reflect the tremendous scatter in emissions data. However, virtually, all of the regression coefficients of the normal emitters are significant at least at a 90 percent confidence level. On the other hand, the confidence intervals around the average start emission levels of the high emitters are quite large due to high scatter and small sample sizes.

Shown below for illustration purposes is a sample calculation of start emissions. It illustrates the soak function equations and methodology shown in Section 5.

Example: Calculate HC start emissions at a soak time of 88 minutes for a 1991 model year PFI-equipped car with 60,000 miles.

Start Emissions (@88min) = Basic Start Emissions (@12hr) * Soak Function

From Tables 4a, 5a and A-1:
Basic Start Emissions = High_ave * Highs + Norm_ave * Normals

START = 4.829*0.0987 + (1.999 + 0.00683*60)(1.0 - 0.0987) = 2.647 g HC

Soak Function = California Soak Funct * [Ratio+(1-Ratio)*((SoakTime-10)/(X-10))]

From Table 6, using the coefficients for catalyst-equipped vehicles:
California Soak Funct = 0.000 + (0.01272)*(88) + (-6.30E-05)*$(88)^2$ = 0.63149

Ratio = (Start@10min / Start@12hr) / California Soak Funct@10min
= 1.3234 for HC as given in Section 5.0

SoakTime = 88 minutes

X = 89 minute HC time domain (from Table 6).

Soak Function = 0.63149 * [1.3234 + (1-1.3234) * ((88-10) / (89-10))] = 0.63407

Start Emissions(@90min) = 2.647 * 0.63407 = 1.679g HC

New Data Update

No new data have been incorporated into this analysis since the initial Draft release of this document.

Response to Stakeholder and Peer Review Comments

Significant stakeholder comments were not received for this document. However, three separate paid and independent peer reviewers were used, and provided the following comments. Their comments were either addressed directly in the document or are discussed below.

1. One reviewer questioned the inclusion of the API vehicle test data solely on the basis of its higher mileage nature. He felt that the different geographical location of the testing and sampling, and potentially different recruitment techniques may add uncertainty to the results.

   In response, EPA feels that these geographical differences should be minimal, and that API followed reasonable and traditional recruitment and testing methods. In addition, the inclusion of these data provide largely unique and sorely needed information on higher mileage vehicles.

2. In regards to the Start Soak Adjustment, one reviewer expressed concern about the use of two data points to adjust the entire continuum of soak time emission effects.

   This is certainty a valid concern. However, the only data outside of the special CARB study which were available are at the FTP soak time values of 10 minutes and 720 minutes. To help overcome this lack of data, the CARB study model is used to fill in these blanks.

3. One reviewer stressed the need for the regression statistics to be reported in an easily readable table. This will allow subsequent reviewers to determine the uncertainty in the final results.

   These are now provided in Appendix B in Tables B-1 through B-8.

4. The remaining comments presented by the Peer reviewers which could not be incorporated into this document largely pertain to suggestions that more testing and data analysis are needed. In particular more information is needed to better

characterize the behavior of high emitters, and develop more robust statistics. They also stressed that additional data should be obtained on start soak periods between the extremes of 10 minutes and 720 minutes to better validate the model.

EPA agrees on these points. However, such data collection efforts and analysis will likely have to wait for the next generation of MOBILE models.

Appendix A
Fraction of High and Normal Emitters in the Fleet

This appendix shows the fraction of HC and CO high and normal emitters in the fleet for start emissions. High emitter fractions for NOx emissions are not shown because only normal emitters are assumed to exist for NOx start emissions (data suggested that high NOx emissions rarely occur during cold start). This Appendix also briefly discusses the methodology and rational for the high emitter adjustment factor for recruitment bias.

Tables A-1 and A-2 show the fraction of HC and CO high emitters in the fleet after they have been adjusted for recruitment bias. The use of these to develop start emission factors are discussed in Section 4.4 and Section 4.5. The derivation of these high emitter fractions and the average High and Normal emitter emission factors is discussed in detail in EPA document M6.IM.001. However, a brief description and the mathematical equation is shown below.

The number of High and Normal emitters is calculated at each age point for each combination of vehicle type / pollutant / model year / technology group using the following general equations.

Where:

‘Highs’ is the fraction of High emitters.
‘Normals’ is the fraction of Normal emitters.
‘RLA4' is the average running emission rate, after adjustment based on IM240 data from Dayton, OH.
‘High_ave’ is the high emitter running emission average estimated from the FTP data.
‘Norm_ave’ is the normal emitter running emission average estimated from the FTP data.

Highs + Normals = 1 Eqn A-1

and

RLA4 = High_ave * Highs + Norm_ave * Normals Eqn A-2

Solving for the variables Highs and Normals produces:

Highs = (RLA4 - Norm_ave) / (Highave - Norm_ave) Eqn A-3

Normals = 1 - Highs Eqn A-4

Recruitment Bias Discussion

The theoretical justification for the FTP recruitment bias rests on anecdotal observations from test programs over the years that sample vehicles recruited by EPA or a major automaker will be disproportionately lower in high emitters. This is because owners who will participate in a test program are less likely to tamper or deliberately mal-maintain their vehicle than are owners who decline to participate. This may result from the fear exposure by a Federal agency for an act which is illegal (tampering the emission controls on a vehicle). The other bias which is likely present in the EPA and automaker data is the tendency to recruit relatively low mileage vehicles at the expense of high mileage vehicles. These low mileage vehicles are frequently a test priority for an automaker due to warranty and recall concerns. This type of sampling bias leads to a well characterized sample with mileages less than 50,000 miles, but a more poorly characterized sample with higher mileages.

To experimentally verify the potential high emitter recruitment bias, a large amount of in-use IM240 data from the Dayton, Ohio I/M program (211,000 initial tests) were obtained. These data were used to investigate and correct the recruitment bias believed to be inherent in the FTP type data. Since the Dayton sample contains virtually the entire vehicle fleet (or a randomly selected 50 percent) of the city these issues of recruitment bias should be minimal. For example, the sample size is quite large (211,000 vehicles). Even if high emitters are just a few percent of this sample, they should be well characterized. Also, I/M is not a voluntary program in Ohio; thus, a motorist cannot simply decline to participate; however, they can illegally evade the program by registering outside of the program boundary. It was suggested by some reviewers, that the program evaders could range from 1 percent to 5 percent of the total fleet.

Although the mileage data from Dayton are highly suspect and not useful, the vehicles of a given model year vintage are older than the vehicles of the same model year vintage in the EPA and AAMA databases because the Dayton testing was done subsequent to the EPA and AAMA testing. Thus, the Dayton data should provide a more representative cross-section of the in-use fleet. The derivation of the average running emission rates, with the adjustments based on the Dayton IM240 data, are discussed in EPA document M6.EXH.001.

The high emitter recruitment adjustment factor is documented in EPA report M6.EXH.001 in detail. In terms of start emissions it had a tendency to increase the fraction of high emitters in the fleet by a few percent. The impact of this was slightly higher on start emissions factors.

Table A-1
Estimated Fraction of HC High Emitters in the Fleet

	HC	HC	HC	HC	HC	HC	HC
MILEAGE	**88-93 PFI**	**88-93 TBI**	**83-87 FI**	**86-89 Carb**	**83-85 Carb**	**81-82 FI**	**81-82 Carb**
2.142	0.0184	0.0239	0.0223	0.0052	0.0232	0.0203	0.0282
12.823	0.0227	0.0251	0.0157	0.0197	0.0158	0.0654	0.0543
29.335	0.0422	0.0270	0.0406	0.0526	0.0047	0.1613	0.1580
50	0.0800	0.0386	0.1003	0.1042	0.0917	0.2861	0.2906
60.006	0.0987	0.0458	0.1298	0.1296	0.1348	0.3485	0.3560
74.239	0.1260	0.0561	0.1723	0.1661	0.1972	0.4393	0.4503
87.786	0.1525	0.0661	0.2078	0.2012	0.2578	0.5275	0.5416
100.01	0.1770	0.0753	0.2346	0.2334	0.3135	0.6094	0.6253
112.948	0.2036	0.0851	0.2634	0.2678	0.3737	0.6986	0.7152
124.625	0.2280	0.0940	0.2898	0.2992	0.4290	0.7812	0.7976
135.738	0.2518	0.1026	0.3153	0.3295	0.4826	0.8620	0.8772
146.315	0.2748	0.1110	0.3400	0.3586	0.5345	0.9407	0.9539
156.38	0.2972	0.1190	0.3638	0.3866	0.5847	1.0000	1.0000
165.96	0.3189	0.1267	0.3868	0.4135	0.6332	1.0000	1.0000
175.077	0.3398	0.1341	0.4089	0.4393	0.6801	1.0000	1.0000
183.753	0.3601	0.1412	0.4303	0.4641	0.7253	1.0000	1.0000
192.01	0.3798	0.1480	0.4508	0.4879	0.7690	1.0000	1.0000
199.869	0.3988	0.1546	0.4706	0.5108	0.8111	1.0000	1.0000
207.349	0.4171	0.1609	0.4896	0.5327	0.8516	1.0000	1.0000
214.466	0.4348	0.1669	0.5079	0.5537	0.8907	1.0000	1.0000
221.241	0.4519	0.1727	0.5255	0.5738	0.9284	1.0000	1.0000
227.688	0.4683	0.1782	0.5425	0.5931	0.9646	1.0000	1.0000
233.823	0.4842	0.1836	0.5587	0.6116	1.0000	1.0000	1.0000
239.663	0.4994	0.1887	0.5743	0.6293	1.0000	1.0000	1.0000
245.22	0.5141	0.1936	0.5893	0.6462	1.0000	1.0000	1.0000
250.509	0.5283	0.1982	0.6036	0.6624	1.0000	1.0000	1.0000

Table A-2
Estimated Fraction of CO High Emitters in the Fleet

MILEAGE	CO 88-93 PFI	CO 88-93 TBI	CO 83-87 FI	CO 86-89 Carb	CO 83-85 Carb	CO 81-82 FI	CO 81-82 Carb
2.142	0.0093	0.0552	0.0180	0.0103	0.0130	0.0119	0.0508
12.823	0.0082	0.0553	0.0123	0.0388	0.0093	0.0511	0.1102
29.335	0.0241	0.0553	0.0357	0.0929	0.0473	0.1334	0.2441
50	0.0458	0.0554	0.0889	0.1741	0.1783	0.2466	0.4138
60.006	0.0566	0.0555	0.1150	0.2140	0.2430	0.3024	0.4969
74.239	0.0721	0.0555	0.1496	0.2715	0.3364	0.3830	0.6163
87.786	0.0872	0.0556	0.1765	0.3270	0.4271	0.4611	0.7312
100.01	0.1010	0.0556	0.2012	0.3778	0.5102	0.5327	0.8360
112.948	0.1159	0.0557	0.2276	0.4323	0.5998	0.6097	0.9479
124.625	0.1296	0.0558	0.2518	0.4822	0.6819	0.6802	1.0000
135.738	0.1429	0.0558	0.2751	0.5302	0.7614	0.7484	1.0000
146.315	0.1556	0.0559	0.2976	0.5764	0.8381	0.8141	1.0000
156.38	0.1680	0.0559	0.3193	0.6210	0.9121	0.8775	1.0000
165.96	0.1799	0.0560	0.3402	0.6638	0.9836	0.9387	1.0000
175.077	0.1914	0.0560	0.3602	0.7050	1.0000	0.9976	1.0000
183.753	0.2025	0.0561	0.3795	0.7445	1.0000	1.0000	1.0000
192.01	0.2132	0.0561	0.3981	0.7825	1.0000	1.0000	1.0000
199.869	0.2235	0.0561	0.4159	0.8191	1.0000	1.0000	1.0000
207.349	0.2334	0.0562	0.4330	0.8541	1.0000	1.0000	1.0000
214.466	0.2429	0.0562	0.4495	0.8877	1.0000	1.0000	1.0000
221.241	0.2521	0.0562	0.4653	0.9200	1.0000	1.0000	1.0000
227.688	0.2609	0.0563	0.4804	0.9510	1.0000	1.0000	1.0000
233.823	0.2693	0.0563	0.4949	0.9806	1.0000	1.0000	1.0000
239.663	0.2774	0.0563	0.5089	1.0090	1.0000	1.0000	1.0000
245.22	0.2852	0.0564	0.5222	1.0363	1.0000	1.0000	1.0000
250.509	0.2927	0.0564	0.5350	1.0623	1.0000	1.0000	1.0000

Appendix B

Statistical Detail: Standard Errors, P values and Standard Deviations

Table B-1
Standard Deviations of Means
START Emissions of High Emitter CARS

MY Group	Tech Group	HC Sample Size	CO Sample Size	HC Standard Deviation	CO Standard Deviation	NOx Standard Deviation
1988-93	PFI*	25	30	5.84	73.73	N/A
1988-93	TBI	25	30	5.84	73.73	N/A
1983-87	FI***	103	124	10.39	92.75	N/A
1986-89	Carb**	371	350	23.89	83.21	N/A
1983-85	Carb	371	350	23.89	83.21	N/A
1981-82	FI	103	124	10.39	83.21	N/A
1981-82	Carb	371	350	23.89	83.21	N/A

* 1988-93 PFI and TBI combined together for a total sample size of 3
** 1986-89 Carb, 1983-85 Carb and 1981-83 Carb combined together for a total sample size of 350 or 371
*** 1983-87 FI and 1981-82 FI combined together for a total sample size of 124 or 103

Table B-2
Standard Deviations of Means
START Emissions of High Emitter TRUCKS

MY Group	Tech Group	HC Sample Size	CO Sample Size	HC Standard Deviation	CO Standard Deviation	NOx Standard Deviation
1988-93	PFI	3*	3	5.10	68.29	N/A
1988-93	TBI	3	3	5.10	68.29	N/A
1981-87	FI	4	18	5.30	115.30	N/A
1984-93	Carb	12	19	8.81	93.90	N/A
1981-83	Carb	17	23	13.72	116.09	N/A

* 1988-93 PFI and TBI combined together for a total sample size of 3

Table B-3
Regression Statistics from Normal Emitting Cars - CO EMISSIONS

MY Group	Tech Group	Sample Size	S.E Slope	SE ZML	Sig T Slope	Sig T ZML
		CO	CO	CO	CO	CO
1988-93	PFI	1591	0.01618	0.6688	0.1897	0.000
1988-93	TBI	433	0.02424	1.0846	0.9624	0.000
1983-87	FI	641	0.01600	0.9760	0.7870	0.000
1986-89	Carb	94	0.06987	4.4534	0.1206	0.000
1983-85	Carb	234	0.06328	2.4836	0.0960	0.000
1981-82	FI	108	0.09004	4.4260	0.0038	0.000
1981-82	Carb	816	0.03257	1.3539	0.0000	0.000

Table B-4
Regression Statistics from Normal Emitting Cars - HC EMISSIONS

MY Group	Tech Group	Sample Size	S.E Slope	SE ZML	Sig T Slope	Sig T ZML
		HC	HC	HC	HC	HC
1988-93	PFI	1583	0.00115	0.0475	0.0002	0.000
1988-93	TBI	436	0.00205	0.0914	0.1092	0.000
1983-87	FI	623	0.00100	0.0860	0.3450	0.000
1986-89	Carb	92	0.00351	0.2172	0.000	0.000
1983-85	Carb	234	0.00376	0.1469	0.0130	0.000
1981-82	FI	105	0.00391	0.1948	0.0313	0.000
1981-82	Carb	839	0.00184	0.0775	0.000	0.000

Table B-5
Regression Statistics from Normal Emitting Cars - NOX EMISSIONS

MY Group	Tech Group	Sample Size	S.E Slope	SE ZML	Sig T Slope	Sig T ZML
		NOX	NOX	NOX	NOX	NOX
1988-93	PFI	1611	0.00122	0.0509	0.1064	0.000
1988-93	TBI	441	0.00328	0.1467	0.5472	0.000
1983-87	FI	694	0.00100	0.0760	0.2460	0.000
1986-89	Carb	95	0.00345	0.2215	0.5311	0.000
1983-85	Carb	248	0.00328	0.1347	0.1113	0.000
1981-82	FI	108	0.00368	0.1808	0.8725	0.000
1981-82	Carb	974	0.00157	0.0708	0.0000	0.000

Table B-6
Regression Statistics from Normal Emitting TRUCKS - CO EMISSIONS

MY Group	Tech Group	Sample Size	S.E Slope	SE ZML	Sig T Slope	Sig T ZML
		CO	CO	CO	CO	CO
1988-93	PFI	330	0.00410	0.1993	0.2870	0.0000
1988-93	TBI	464	0.00363	0.1550	0.0003	0.0000
1981-87	FI	76	0.00477	0.3028	0.0467	0.0000
1984-93	Carb	115	0.00857	0.4228	0.3220	0.0000
1981-83	Carb	157	0.01256	0.5563	0.9020	0.0000

Table B-7
Regression Statistics from Normal Emitting TRUCKS - HC EMISSIONS

MY Group	Tech Group	Sample Size	S.E Slope	SE ZML	Sig T Slope	Sig T ZML
		HC	HC	HC	HC	HC
1988-93	PFI	329	0.0514	2.496	0.744	0.0000
1988-93	TBI	465	0.0542	2.314	0.009	0.0000
1981-87	FI	90	0.0844	5.783	0.407	0.0000
1984-93	Carb	122	0.2009	10.434	0.204	0.0000
1981-83	Carb	163	0.1920	8.671	0.094	0.0000

Table B-8
Regression Statistics from Normal Emitting TRUCKS - NOX EMISSIONS

MY Group	Tech Group	Sample Size	S.E Slope	SE ZML	Sig T Slope	Sig T ZML
		NOX	NOX	NOX	NOX	NOX
1988-93	PFI	331	0.00282	0.137	0.179	0.0000
1988-93	TBI	466	0.00541	0.233	0.549	0.0000
1981-87	FI	93	0.00315	0.219	0.020	0.0000
1984-93	Carb	132	0.00498	0.276	0.382	0.6044
1981-83	Carb	166	0.00642	0.293	0.081	0.0003