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Development of an Improved Computer Simulation of Vehicle Emissions During Cold Start and Warm-Up Operation

prepared for:

U.S. Environmental Protection Agency
Office of Mobile Sources
Certification Division

September 30, 1991

prepared by:

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Development of an Improved Computer Simulation of Vehicle Emissions During Cold Start and Warm-up Operation

Prepared Under EPA Contract No. 68-C9-0053
Work Assignment 1-02

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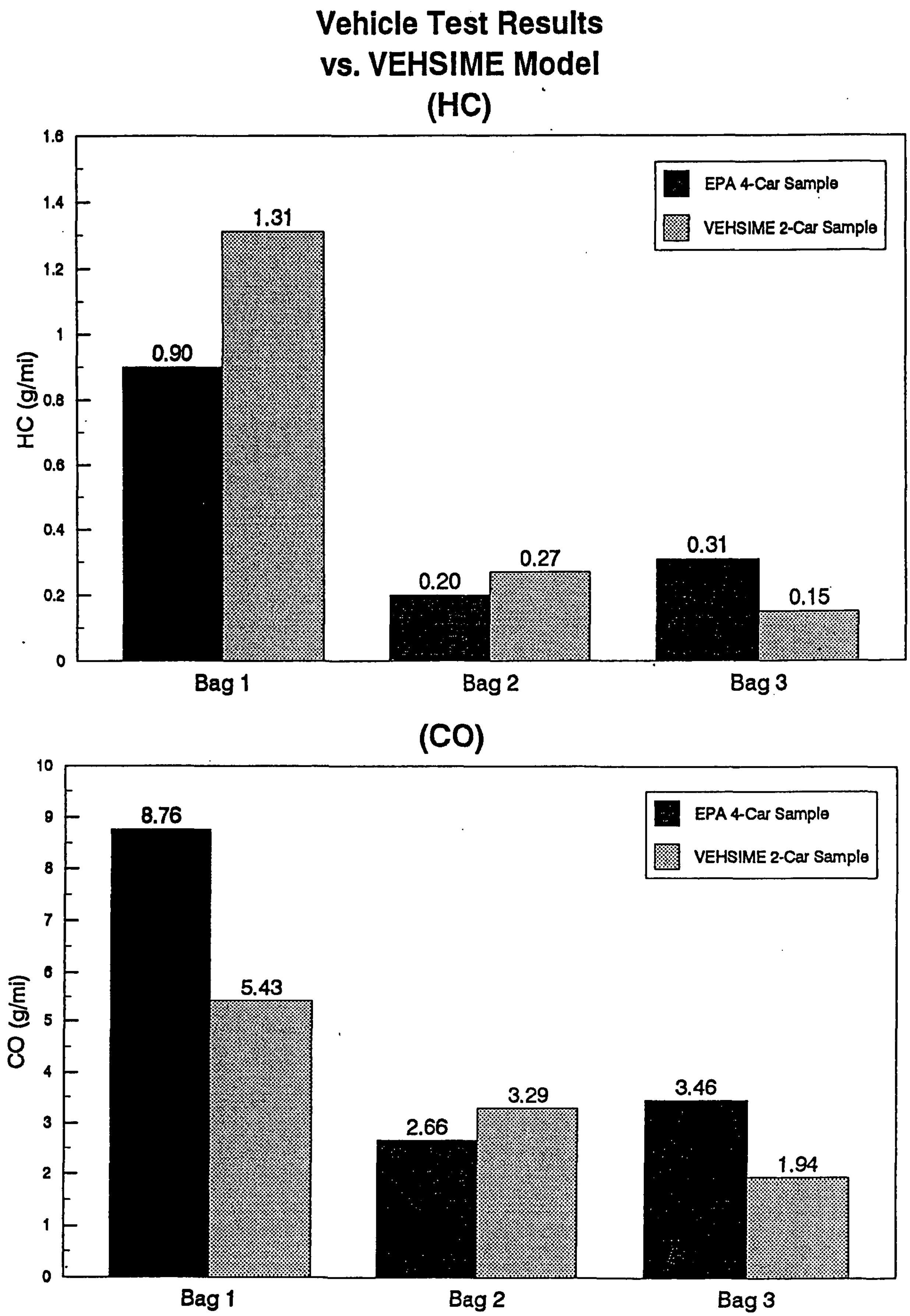
1. Summary

Based on an analysis of modal emissions data from vehicles tested by EPA, an algorithm has been developed to simulate cold start and warm-up operation using a vehicle emissions simulation model called VEHSIME. During the first 450 seconds of operation following a cold start, the algorithm applies correction factors to the emission rates contained in "map" of emission rates over the full speed and load range of a warmed-up engines. The correction factor increases "engine-out" HC and CO emissions in proportion to the number of seconds left in the warm-up period. The algorithm also applies a catalyst efficiency factor to the map of engine-out emissions as soon as the fuel consumption since start up reaches the cumulative fuel consumption associated with the catalyst reaching "light-off" temperature on the LA4 cycle (120 seconds into the cycle). The catalyst efficiency factor is computed from the difference between the engine-out and tailpipe emission maps for the engine being used for the simulation.

Figure 1 shows how the Federal Test Procedure (FTP) emissions results for four vehicles tested by EPA compare to emissions predicted by the VEHSIME model for two hypothetical vehicles using two different engines for which warmed up emissions maps were available. (Modal emissions test results from the same four vehicles tested by EPA were used to develop the cold start algorithm added to VEHSIME.) As the figure shows, the VEHSIME model with the cold start algorithm produces reasonable estimates of emissions during each "bag" of the FTP. The differences between the results predicted by the VEHSIME model and the average of the four vehicles tested by EPA are within the range of the differences between the four vehicles themselves.

Although further data are needed to determine how accurate the new cold start algorithm is for cycles other than the FTP, the algorithm in its present form already provides a useful tool for estimating the emissions during periods of travel from a cold start that are shorter in length than the first bag of the FTP (3.59 miles). This capability is necessary for accurately estimating emissions in parking lots and other places where emissions are likely to be substantially higher than the average emissions that occur during the first eight minutes of operation on the LA4 cycle. The ability to accurately predict short trip emission results can also contribute to improved estimates of emissions inventories for whole metropolitan areas through the use of more detailed information regarding the distribution of trips by trip length. (Under the current procedures for estimating vehicle emissions, vehicle emissions are assumed to be independent of trip length.)

Figure 1


Vehicle Test Results
vs. VEHSIME Model
(HC)
HC (g/mi)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
EPA 4-Car Sample
VEHSIME 2-Car Sample
0.90
1.31
0.20
0.27
0.31
0.15
Bag 1
Bag 2
Bag 3
(CO)
CO (g/mi)
10
9
8
7
6
5
4
3
2
1
0
EPA 4-Car Sample
VEHSIME 2-Car Sample
8.76
5.43
2.66
3.29
3.46
1.94
Bag 1
Bag 2
Bag 3

2. Introduction

Under Contract No. 68-C9-0053, Sierra Research, Inc. (Sierra) provides a variety of analytical services for the Certification Division of the U.S. Environmental Protection Agency's Office of Mobile Sources. Under Work Assignment No. 1-02 of the contract, Sierra was directed to analyze emissions data previously collected by EPA and to use the results of the analysis to develop an improved technique for simulating vehicle emissions during cold start and warm-up operation using a vehicle emissions simulation model called "VEHSIME" (pronounced "vee'-syme").

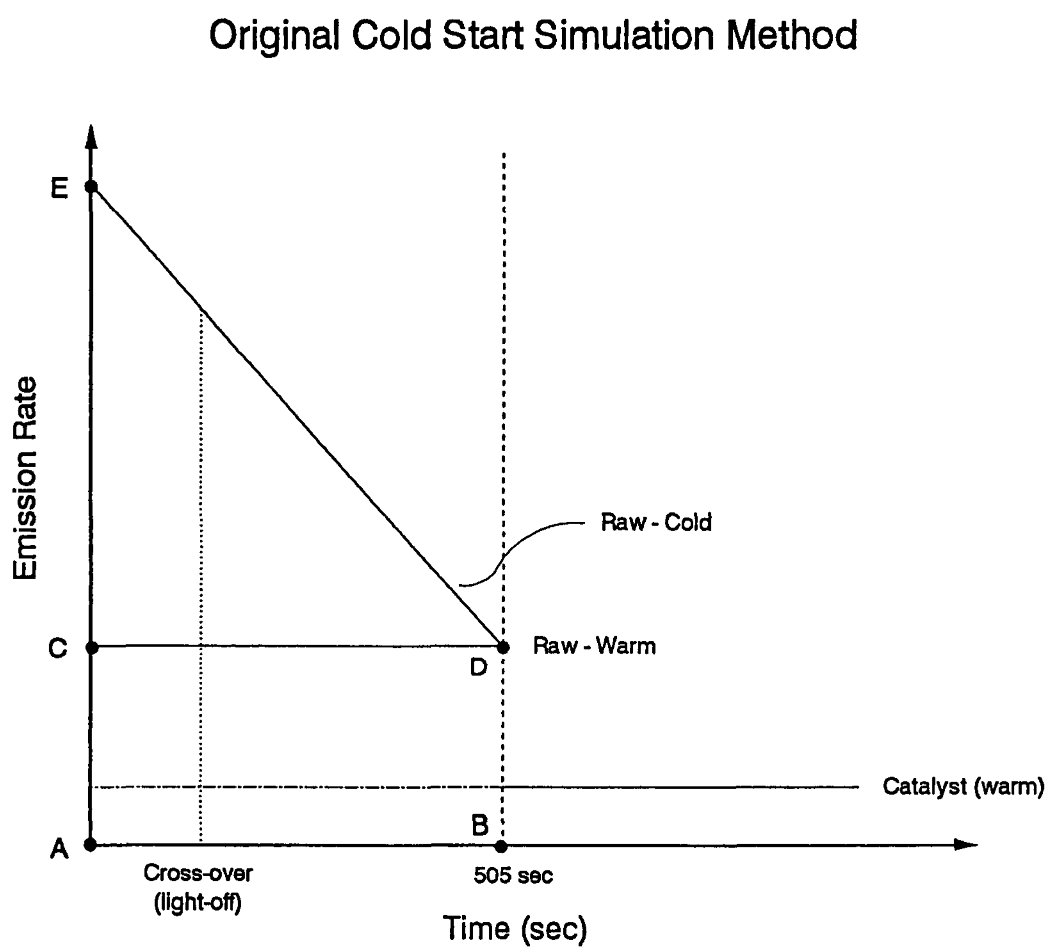
Background

One concern with the representativeness of the current test procedure for the emission testing of light-duty vehicles is the extent to which it adequately simulates cold start emissions. With properly maintained late-model cars and light trucks, the emissions that occur prior to catalyst light-off are a substantial portion of the total emissions for the LA4 cycle. The operation of the vehicle during warm-up obviously affects how fast the catalyst reaches operating temperature as well as how much is emitted through the bed of the cold catalyst. The LA4 cycle subjects the vehicle to relatively high-speed freeway operating conditions within three minutes of the cold start. Intuitively, this appears to be a very short period of time between cold start and high load operation which might unrepresentatively affect catalyst warm-up.

Since vehicle emissions are extremely sensitive to vehicle operating conditions, obtaining accurate estimates of emissions in various geographic areas depends on the ability to estimate the effect of driving pattern differences between regions. Historically, EPA has attempted to estimate area-specific vehicle emissions through the application of speed and temperature correction factors to data generated with the standard test procedures. Such factors are incorporated within the MOBILE4 computer model. However, the correction factors built into the model were developed by interpolating and extrapolating "hot start" test results for the LA4 compared to other speed-time traces, such as the New York City Cycle and the Highway cycle. The speed correction factors built into the MOBILE4 model are based on the assumption that the significance of cold start emissions is independent of variations in driving pattern. To incorporate some consideration of how changes in driving patterns might affect cold start and warm-up emissions, EPA has been interested in developing a computer model that can simulate such cold start and warm-up operation over any specified speed-time profile.

Under a previous work assignment, Sierra developed a simplistic technique to estimate motor vehicle emissions during cold start and warm-up operation using the engine-map-driven emissions simulation model VEHSIME. (Appendix A contains a description of the model.) In the earlier effort, Sierra used two engine maps, one for tailpipe emissions of a catalyst-equipped engine and one for non-catalytically treated ("raw") emissions from the same engine, and switched from the non-catalyst (raw) map to the catalyst map during the first few minutes of vehicle operation. Additional adjustments included increasing the emissions of the raw map to simulate the higher HC and CO emissions that occur during cold start operation. The increase in emission rates for the raw map at time zero was set such that the area under a straight line drawn between emission rates at time zero and the warmed-up emissions rates at 505 seconds would be representative of the typical ratio of "bag 1" to "bag 3" emissions observed from the testing of non-catalyst vehicles (i.e., 2.23 for HC and 2.50 for CO). This is illustrated graphically in Figure 2. In the case of CO, the emissions rate at time zero for each element of the engine map (represented by "E", in the figure) was set so that the area enclosed by the polygon ABDE was 2.50 times the area enclosed by the rectangle ABCD.

Figure 2



Under the previous work assignment, the VEHSIME model was modified so that emissions began being computed using the map for catalytically treated emissions from a warmed up engine at the point necessary to have the ratio of "Cold FTP/Hot FTP" emissions ([bag 1 + bag 2] ÷ [bag 2 + bag 3]) equal to the ratio typical for oxidation catalyst equipped cars (1.89 for HC and 2.25 for CO). That cross-over point turned out to be 122 seconds.

Using the modified version of the VEHSIME model, Sierra investigated the effect of vehicle driving pattern on emissions during the warm-up phase of a trip and determined that total vehicle emissions appear to be strongly influenced by both the driving pattern and the extent to which tailpipe emissions are elevated during the warm-up phase. Based on these preliminary results, it became clear that a more rigorous technique for predicting vehicle emission characteristics during cold start and warm-up would be desirable for accurately estimating the emissions from vehicles in customer service under varying driving patterns.

EPA informed Sierra that increased sophistication of the cold start simulation added to VEHSIME in the earlier work assignment could potentially be achieved by utilizing modal emissions data collected by EPA during 1986 and 1987. Under the EPA testing program, ten different 1984 model vehicles equipped with 3-way catalysts were operated over the standard "LA4" driving cycle while continuous measurements of emission concentrations were made upstream and downstream of the catalyst. On some vehicles, emission measurements were restricted to carbon monoxide. On other vehicles, both HC and CO were measured. Continuous measurements of exhaust system temperatures were made at numerous points in the exhaust system for most of the vehicles. Temperature measurement locations included upstream of the catalyst, at the face of the catalyst, mid-bed of the catalyst, and at the exit of the catalyst. With such data, it is possible to determine how the emissions of the engine and the efficiency of the catalyst changed as a function of elapsed time since start and instantaneous mode of operation. However, all of the available test data were in strip chart form and not in the digitized form needed for efficient computer analysis.

Work Plan Summary

The Work Plan developed for Work Assignment 1-02 consisted of three tasks: 1) Cold Start Simulation Methodology Development, 2) FORTRAN Code Development; and 3) Reporting.

Under Task 1, one subtask was for the development of the algorithm concept and the data analysis approach. Another subtask involved the actual digitizing of strip chart data. The final subtasks were the analysis of the digitized data and the determination of the most appropriate algorithms.

Under this Task 2, the algorithms developed under Task 1 were converted into FORTRAN source code. After debugging and compiling, the code changes were tested to determine how well they matched the raw data from the test vehicles.

The final task involved the preparation of this report and the interim progress reports submitted each month.

###

3. Results

Data Collection and Analysis

Second-by-second continuous emissions test data over the LA4 cycle were acquired from EPA's Catalyst Thermal Activity Test Program (CTAP). Data for 14 vehicles were received in analog strip chart form. The data consisted of volumetric emissions and catalyst temperatures (typically at several locations on the catalyst) as a function of time. Some testing was conducted at both 75°F and 20°F.

The original expectation was that a comprehensive set of technology- and emissions-specific adjustment factors could be developed. Unfortunately, much of the data were incomplete for the purposes of this analysis because:

- Many of the test packets for the 14 vehicles contained only catalyst temperature measurements.

- Of the remaining vehicles, only four had <u>both</u> cold and hot traces for complete LA4-505 cycles with emissions measured both upstream and downstream of the catalyst. (Both cold and hot data were required for the cold start algorithm developed under this effort: a cold start adjustment to a warmed engine map as a function of time. Upstream (i.e., engine out) emissions were needed to develop a cold start adjustment for the engine separate from the catalyst.)

- The emissions data for the four-vehicle sample consisted only of CO concentrations. Limited HC testing was performed on some of the CTAP vehicles but no HC data were available for the 4 vehicles selected. No NOx testing was conducted.

Because of the above-mentioned limitations, the dataset suitable for detailed analysis consisted of the test data described above for the vehicles shown in Table 1.

Using a SummaSketch II digitizing tablet and Fast Cad software, the data were digitized from the strip chart traces and loaded onto Sierra's computer system. For each vehicle in the sample, second-by-second catalyst efficiencies and cold/hot emission ratios were computed as follows:

$$\text{Catalyst Efficiency} = 1 - (\text{Tailpipe Emissions} \div \text{Engine Out Emissions})$$

Cold/Hot Ratio (C/H) =
Cold Engine Out Emissions / Warm Engine Out Emissions

Table 1

Vehicles For Which Both Hot and Cold Start, Upstream and Downstream Data Were Available

Vehicle	Catalyst	Fuel System	O_2 Sensor
1984 Volvo (2.3L)	3-Way	Multi-Pt F.I.	Heated
1984 Volvo (2.3L)	3-Way	Multi-Pt F.I.	Non-Heated
1984 Plymouth (2.2L)	3-Way	Multi-Pt F.I.	Non-Heated
1984 Chrysler (2.2L)	3-Way	Multi-Pt F.I.	Non-Heated

An initial review of the computed catalyst efficiencies and C/H ratios indicated that many of the computed second-by-second catalyst efficiencies were negative. In addition, initial plots of catalyst efficiency and C/H ratio showed large amounts of scatter. Further examination of the emission peaks on the strip charts indicated the negative efficiencies and high scatter were likely caused by a time lag between measurement of engine out and tailpipe emissions. Based on the strip chart data, changes in engine out emissions were being recorded an average of 6 seconds before changes in tailpipe emissions. Some of this time delay would be associated with the time it took emissions to travel from in front of the catalyst to the tailpipe, but most of the delay could have been associated with differences in the sample trains. However, the apparent lag varied up to 2 seconds as a function of the exhaust flow rate, with idle conditions showing the greatest difference between the time changes in emissions were recorded upstream of the catalyst and at the tailpipe.

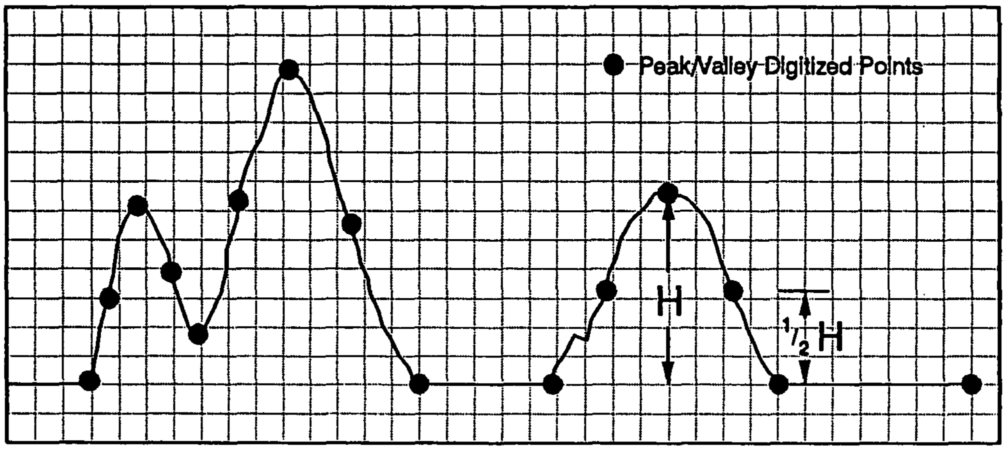
Two separate adjustments were performed on the data in an attempt to remove the scatter caused by the time lag:

1. A fixed lag of 6 seconds was applied to the tailpipe emission traces (i.e., tailpipe concentrations were compared to engine-out concentrations that occurred six seconds earlier).

2. Emission data for the sample vehicles was re-digitized. Instead of digitizing emission levels at regular intervals along the trace (corresponding to the divisions on the time axis of the strip charts), digitizing was performed at the midpoint and the endpoint of each of the emission peaks and valleys as shown in Figure 3. The corresponding points on the tailpipe traces were then digitized and assigned the same time as that indicated on the engine out traces.

Figure 3

"Peak and Valley" Data Digitizing Approach

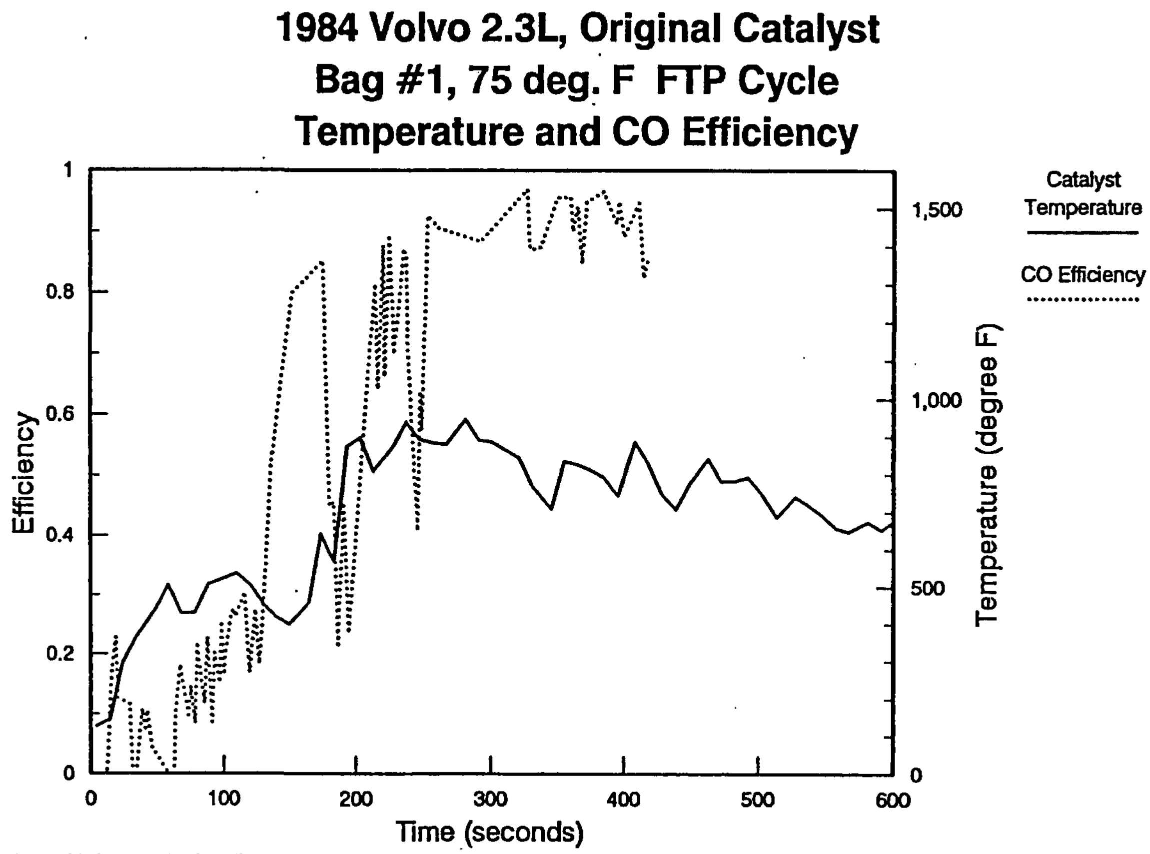


The efficiencies and C/H ratios were re-computed and plotted for both adjusted datasets and compared. Both adjustments produced more well-behaved catalyst efficiencies. C/H ratios computed using the first approach showed much less scatter than those computed using the second approach. This was due to the need to interpolate between the digitized peak/valley points on the hot trace to match the points on the cold trace. All subsequent analysis of the data was therefore based on the use of a fixed lag of 6 seconds applied to the tailpipe emission traces.

Figures 4–7 show the catalyst efficiencies for carbon monoxide for each of the four vehicles. Figures 8–11 show the C/H ratios for the engine-out emissions from the same cars. Some of the "spikes" of low catalyst efficiency and high C/H ratio are believed to be associated with the inaccuracies associated with the assumption that the lag between engine out and tailpipe emissions measurement was a constant 6 seconds.

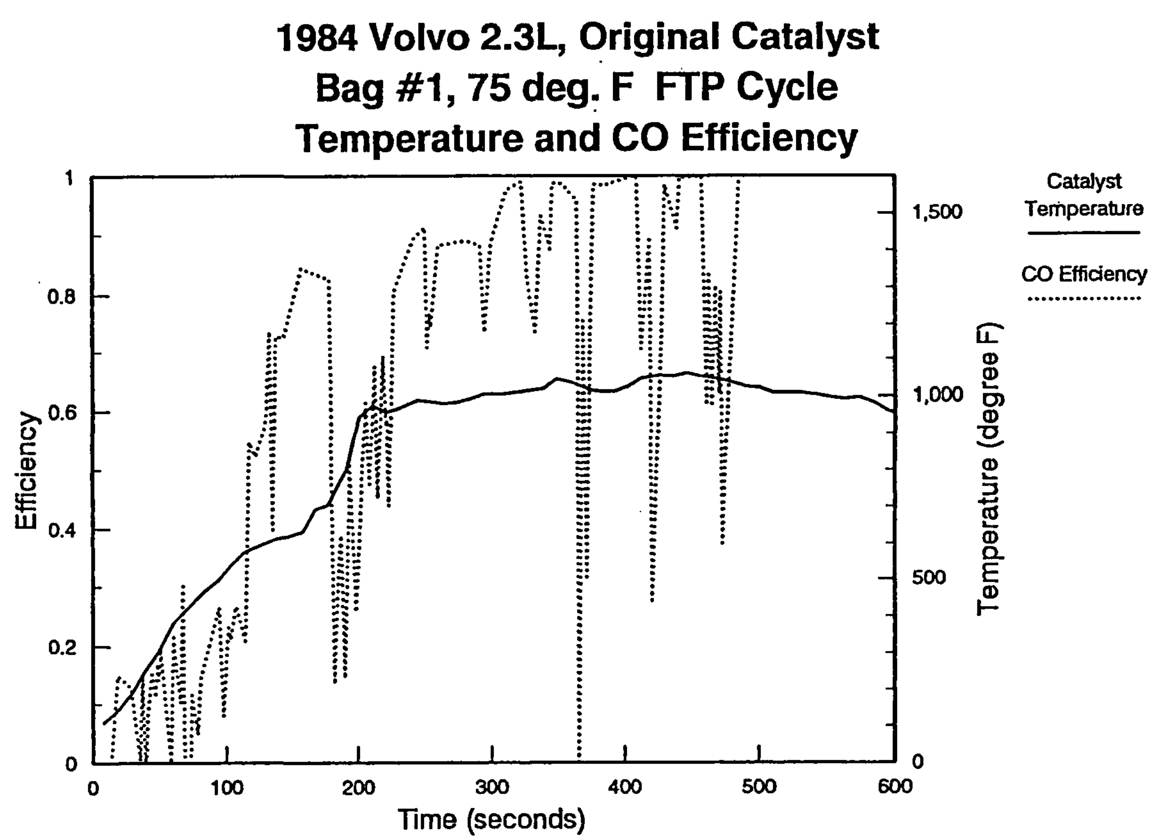
The mean catalyst efficiency and C/H ratios computed for the four-vehicle sample using approach (1) are shown in Figure 12. The data were further smoothed by computing 10 second "moving averages" at each point.

Figure 4



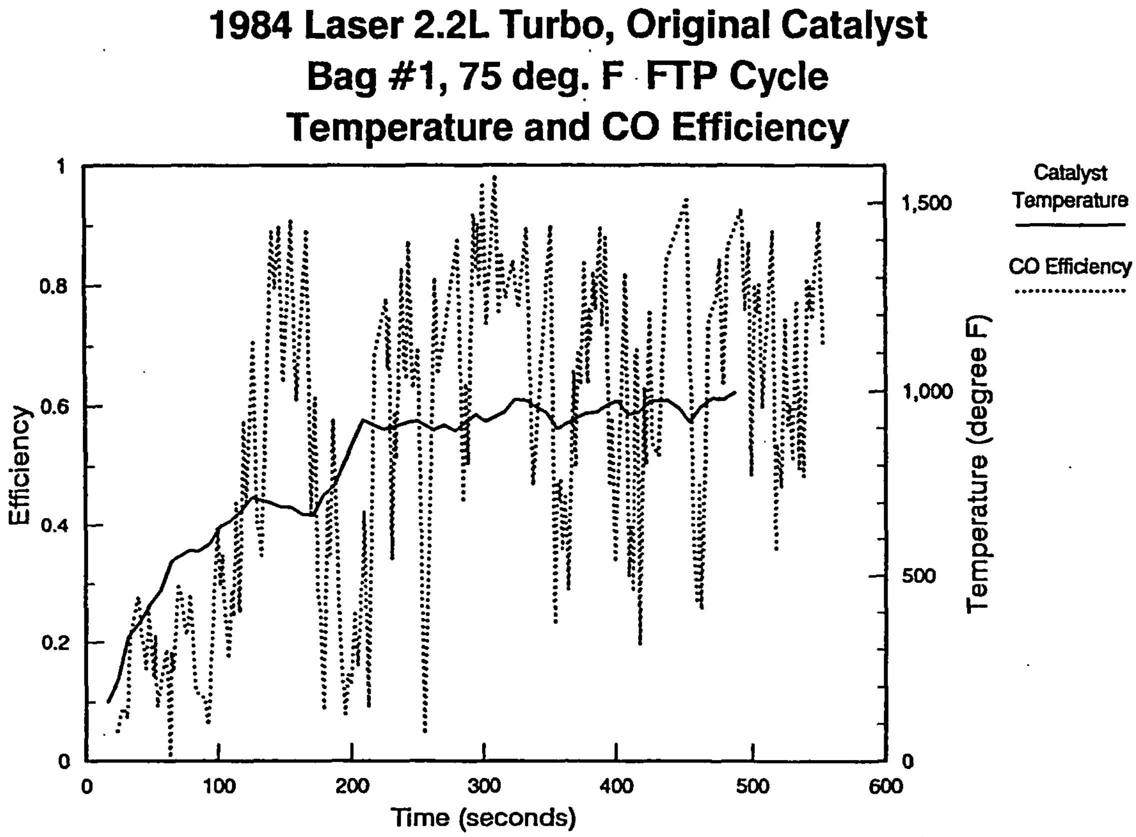
Note: VIN 0156, Packet #13

Figure 5



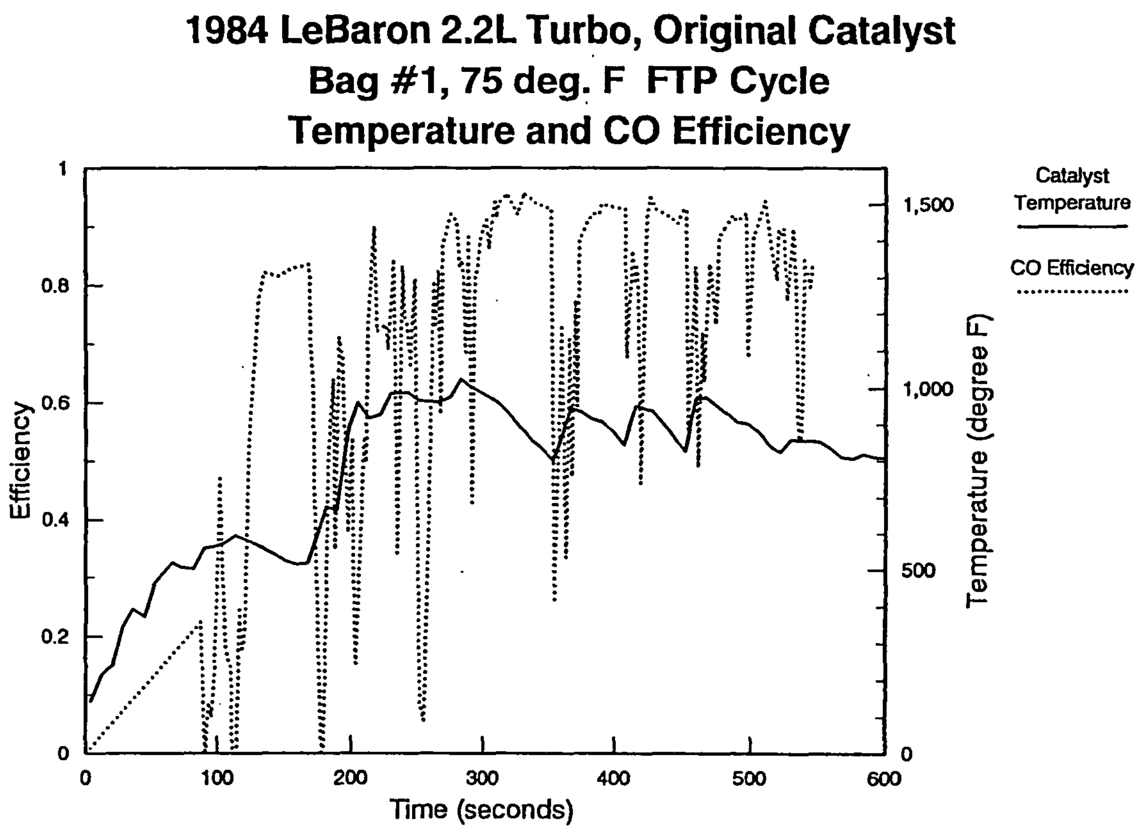
Note: VIN 0192, Packet #17

Figure 6



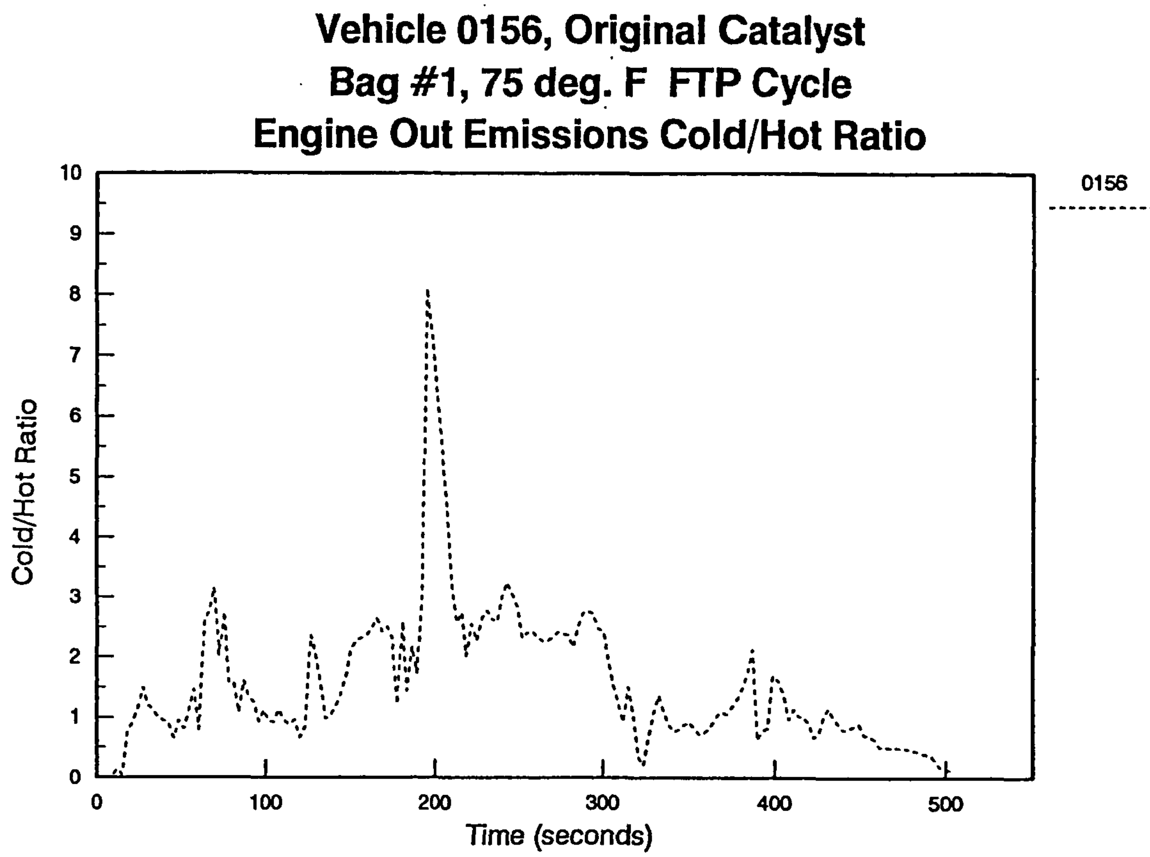
Note: VIN 1115, Packet #10

Figure 7



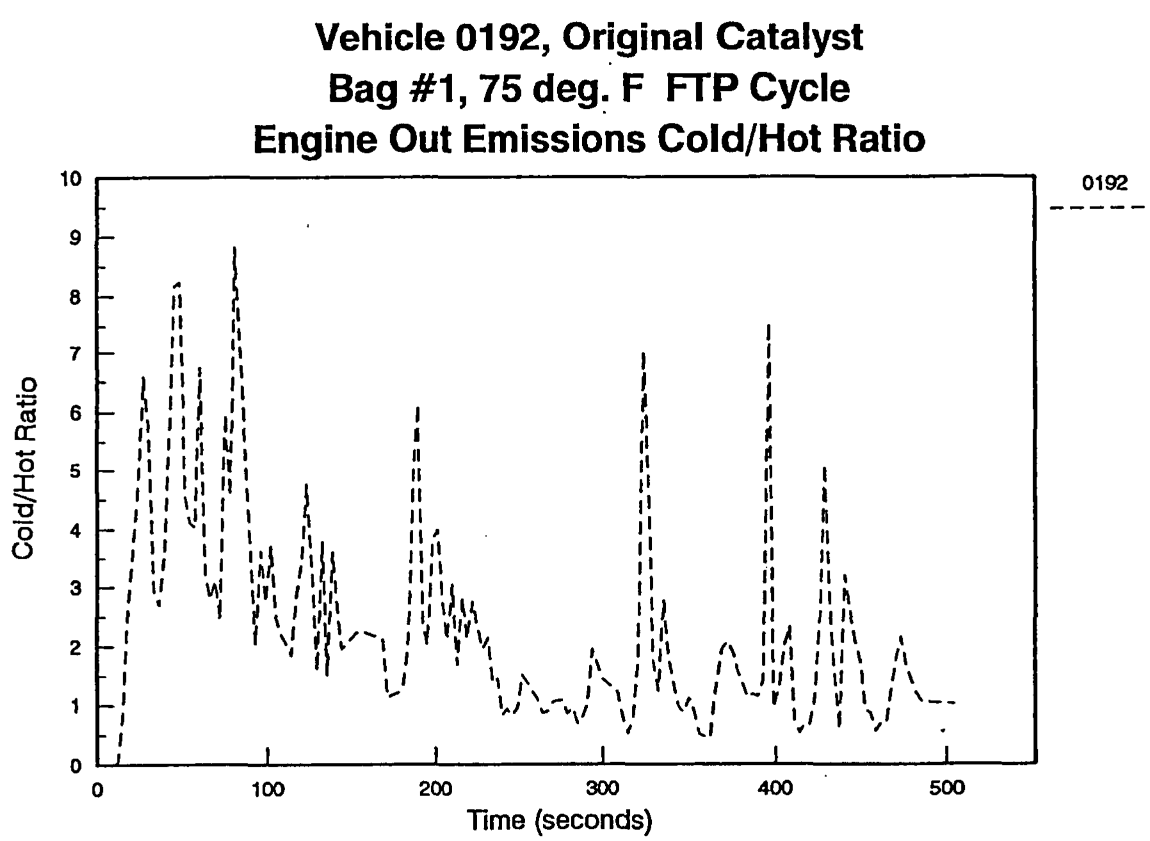
Note: VIN 0196, Packet #8

Figure 8



Note: VIN 0156, Packet #13

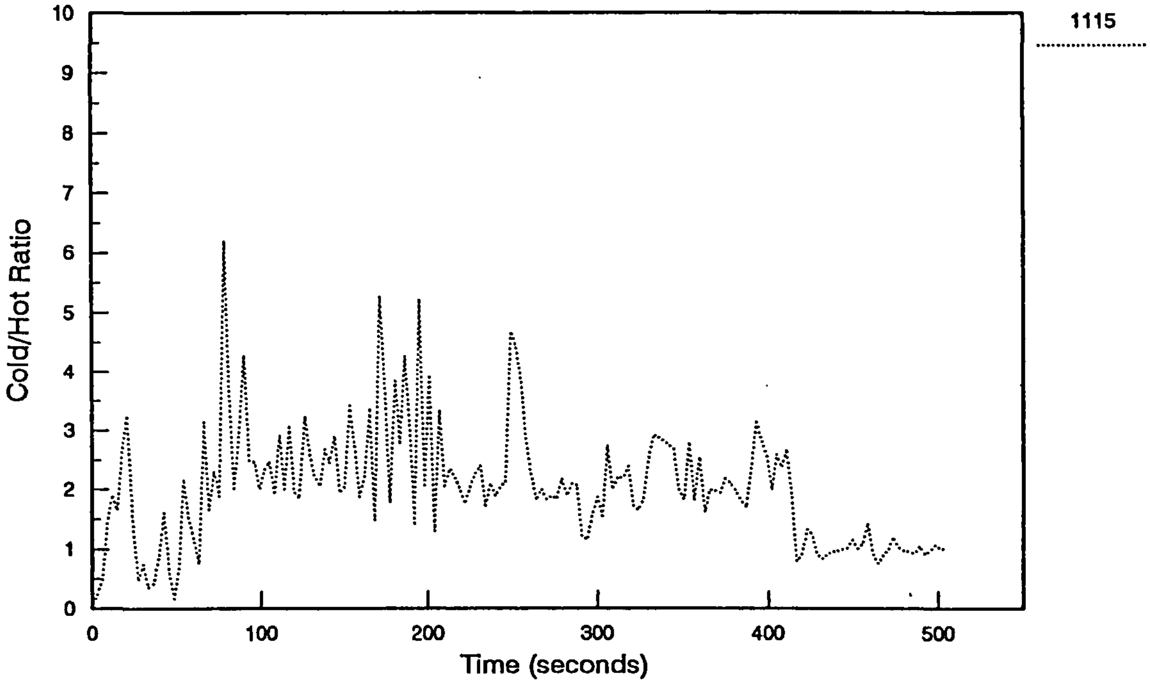
Figure 9



Note: VIN 0192, Packet #17

Figure 10

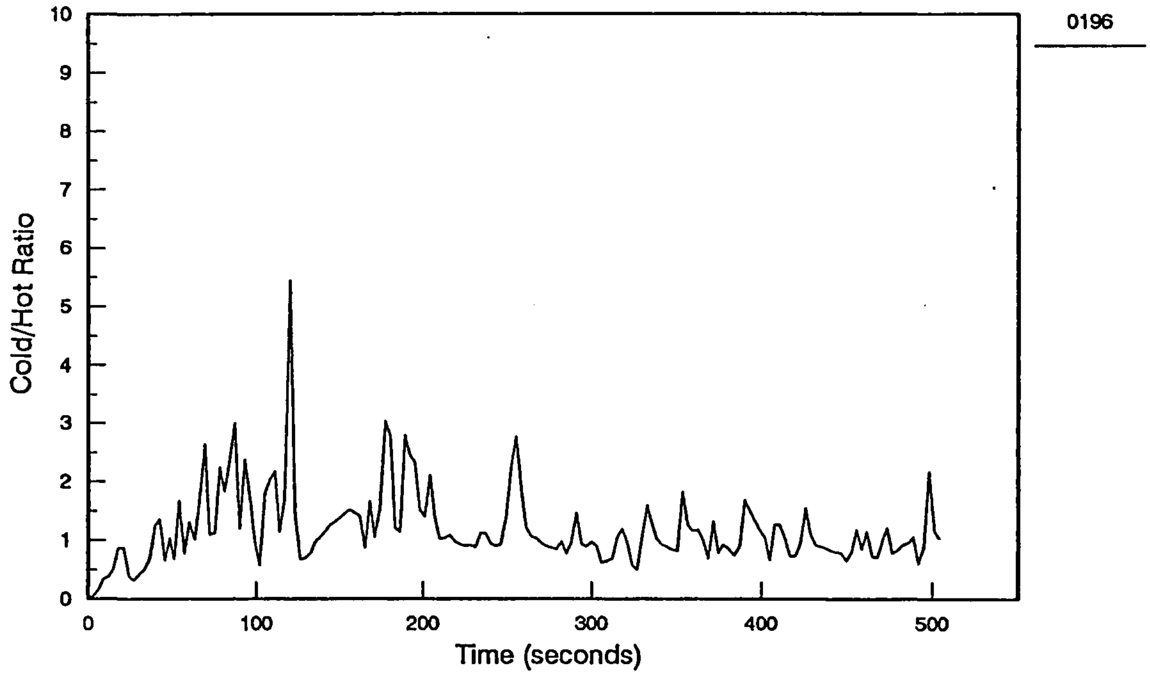
Vehicle 1115, Original Catalyst
Bag #1, 75 deg. F FTP Cycle
Engine Out Emissions Cold/Hot Ratio



Note: VIN 1115, Packet #10

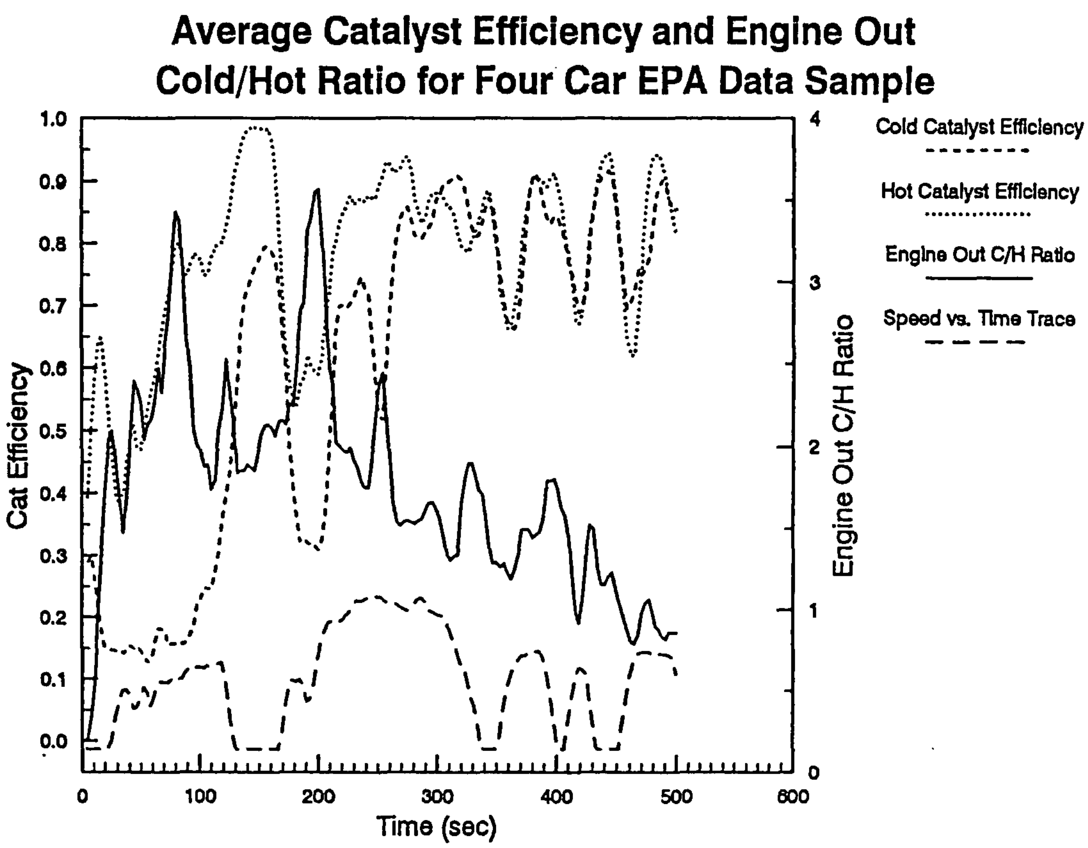
Figure 11

Vehicle 0196, Original Catalyst
Bag #1, 75 deg. F FTP Cycle
Engine Out Emissions Cold/Hot Ratio



Note: VIN 0196, Packet #8

Figure 12



VEHSIME Code Development

Based on the substantially different warm-up characteristics for engines and catalysts that were observed in the modal emissions data, it is apparent that separate cold start adjustment equations for catalyst warm-up and engine warm up are required. Figure 13 shows the warm-up characteristics that were initially selected for coding into the VEHSIME model.

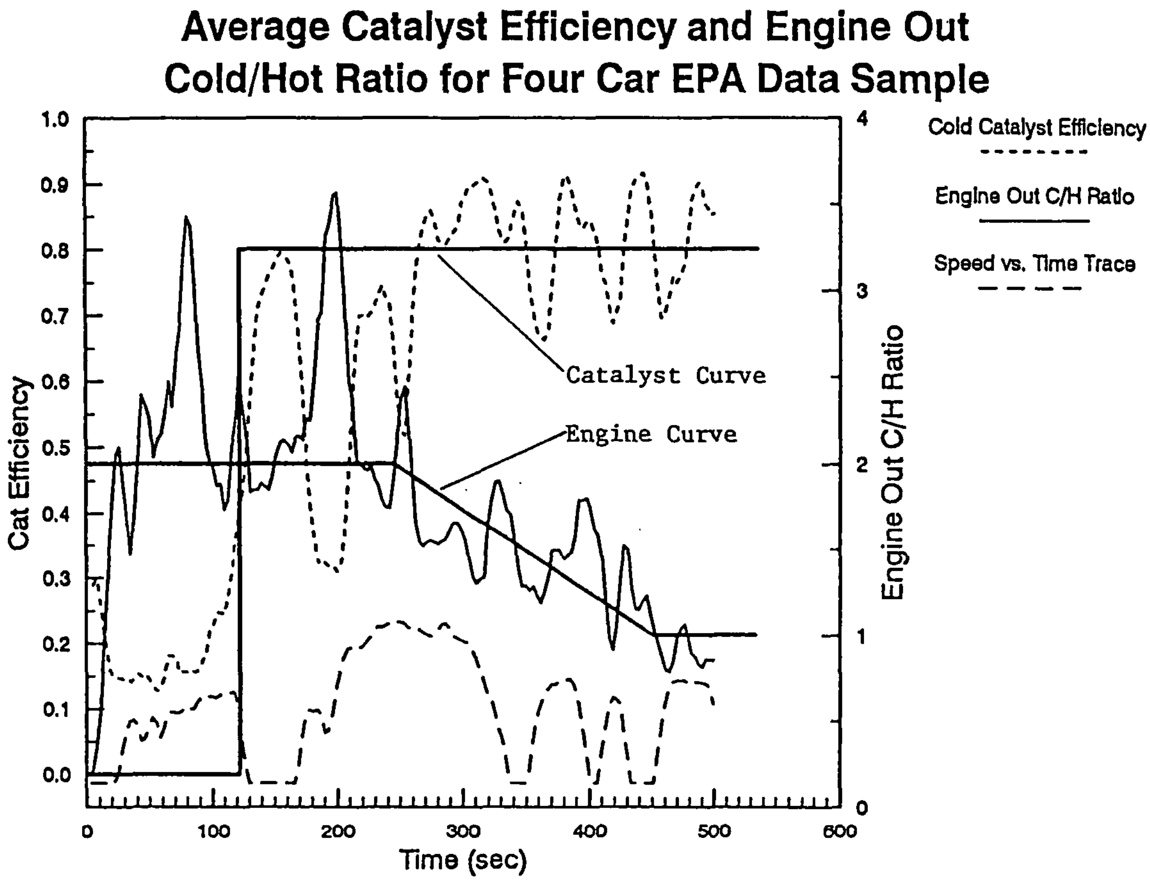
The boldface lines in Figure 13 labeled "Catalyst Curve" and "Engine Curve" represent cold start adjustments due to the catalyst and engine warm-up, respectively. The catalyst curve is a simplified, step function representation of the mean cold start catalyst efficiency of the sample vehicles over time. The engine curve is a linear representation of the mean engine out C/H ratio over time.

Mathematically, the catalyst warm-up and engine warm-up equations as a function of time are:

$$\begin{aligned} CAT(t) &= 0.80 \quad \text{for } t \geq 120 \text{ seconds} \\ &= 0 \quad \text{for } t < 120 \\ &= 2.0 \quad \text{for } t < 245 \text{ seconds} \end{aligned}$$

$$\begin{aligned} ENG(t) &= -0.0049t \quad \text{for } 245 \leq t < 450 \\ &= 1.0 \quad \text{for } t \geq 450 \end{aligned}$$

Figure 13



The VEHSIME model was modified to include a user-invocable cold start subroutine which applies the cold catalyst and engine equations to the engine out emission levels of a fully-warmed engine map as follows:

COLD EMIS(t,RPM,load) = MAP EMIS(RPM,load) x (1-CAT(t)) x ENG(t)

Following some experimentation with the above algorithm, the catalyst efficiency element of the algorithm was refined by substituting the actual catalyst efficiency for each speed-load point computed from the difference between the engine-out and tailpipe emission maps for the individual engines.

Testing the Algorithm

In order to determine whether the cold start algorithm produced reasonable results, VEHSIME simulations were run using engine-out and tailpipe emissions maps available for three oxidation catalyst-equipped engines (a 231 CID Buick, a 140 CID Ford and a 350 CID Chevrolet). A 4,000 pound chassis equipped with an automatic transmission was simulated for the Buick engine. A 3,000 pound chassis with an automatic transmission was simulated for the Ford engine. A 5,000 pound chassis with an automatic transmission was simulated for the Chevrolet engine.

Table 2 shows how the individual bag and composite FTP emissions for the four vehicles tested by EPA compared to the emissions predicted by VEHSIME for the three hypothetical vehicles.

As indicated by the data in Table 2, the predicted performance of the hypothetical vehicle equipped with the 140 CID Ford engine indicates that it is not capable of achieving warmed-up emission levels in the range of those demonstrated by the four vehicles tested by EPA. If that particular engine is excluded from consideration, the average emissions of hypothetical vehicles using the other two engines are quite similar to the average emissions of the vehicles tested by EPA. This similarity was shown graphically in Figure 1 of the Summary section.

Table 2

Four-Car Sample FTP Emissions

Pollutant	Vehicle	Bag 1 (grams)	Bag 2 (grams)	Bag 3 (grams)	Bag 1 (g/mi)	Bag 2 (g/mi)	Bag 3 (g/mi)	Comp FTP (g/mi)	Cold-72 (Bag 1+2) (g/mi)	Hot-72 (Bag 3+2) (g/mi)
HC	0192	4.32	1.24	1.48	1.210	0.323	0.417	0.525	0.741	0.363
	1115	3.15	1.21	1.29	0.882	0.314	0.365	0.440	0.581	0.333
	0156	3.33	0.24	0.99	0.924	0.061	0.274	0.298	0.476	0.164
	0196	2.02	0.35	0.68	0.567	0.090	0.187	0.214	0.316	0.137
CO	0192	31.96	10.21	8.26	8.953	2.659	2.325	3.821	5.623	2.463
	1115	37.07	22.56	21.53	10.384	5.847	6.068	6.770	7.951	5.879
	0156	33.86	3.46	5.71	9.407	0.892	1.587	2.837	4.976	1.223
	0196	22.53	4.89	13.86	6.312	1.255	3.847	2.997	3.656	2.500
NOx	0192	3.00	0.72	1.69	0.839	0.187	0.476	0.396	0.496	0.321
	1115	3.81	2.64	2.96	1.068	0.685	0.834	0.795	0.860	0.747
	0156	4.47	2.97	2.87	1.243	0.764	0.797	0.870	0.992	0.779
	0196	4.48	2.93	3.19	1.255	0.753	0.886	0.890	0.988	0.816

VEHSIM Test Vehicle FTP Emissions

Pollutant	Vehicle	Bag 1 (grams)	Bag 2 (grams)	Bag 3 (grams)	Bag 1 (g/mi)	Bag 2 (g/mi)	Bag 3 (g/mi)	Comp FTP (g/mi)	Cold-72 (Bag 1+2) (g/mi)	Hot-72 (Bag 3+2) (g/mi)
HC	Buick 231	5.04	0.80	0.52	1.404	0.205	0.145	0.435	0.783	0.177
	Chevy 350	4.38	1.30	0.59	1.220	0.332	0.164	0.469	0.761	0.253
	Ford 140	4.78	3.72	2.05	1.331	0.951	0.571	0.926	1.143	0.776
CO	Buick 231	10.97	0.23	3.43	3.056	0.059	0.955	0.920	1.502	0.490
	Chevy 350	28.07	25.51	10.47	7.819	6.524	2.916	5.806	7.177	4.819
	Ford 140	109.09	100.23	63.30	30.387	25.634	17.632	24.429	28.125	21.970
NOx	Buick 231	8.09	5.88	8.12	2.253	1.504	2.262	1.865	1.874	1.877
	Chevy 350	7.45	4.59	7.55	2.075	1.174	2.103	1.613	1.612	1.626
	Ford 140	6.51	3.20	6.31	1.813	0.818	1.758	1.279	1.305	1.278

Conclusions/Recommendations

The data sample on which this algorithm was based is very limited. With only four vehicles, all equipped with fuel-injected, three-way catalyst systems, the development of technology-specific relationships was not possible. Another limitation of the cold start algorithm is that it is being applied to engine maps for carbureted, oxidation catalyst equipped vehicles.

Because of these limitations, and because of the extreme variation in emissions from one vehicle to another, the most appropriate use of the cold start algorithm at the present time may be as a means of developing trip length "correction factors" to be applied to FTP-based emission factors representative of the fleet of vehicles of interest. For example, if the model predicts that CO emissions would be increased by 200% if the trip length is shortened from the length of the FTP to some particular shorter distance, then that change in emission rate should be applied to the FTP emissions rate using the best available emission factors for the fleet in question, rather than the gram per mile values predicted by VEHSIME.

In the future, the algorithm could be refined with the FTP Revision Engine Mapping test data currently being collected by EPA. Under this program, 30 low-mileage vehicles are being steady-state warm and cold engine mapped. With a more robust sample, technology-specific effects may be investigated. A refined algorithm could then be coded into VEHSIME and compared against a representative sample of low-mileage FTP data from surveillance testing or other testing programs.

###

Appendix A

A Description of Sierra's Vehicle Emissions Simulation Model

A Description of Sierra's Vehicle Emissions Simulation Model

VEHSIM, a Vehicle Simulation model, was originally developed by General Motors in the early 1970's to produce a dynamic vehicle simulation incorporating computations of instantaneous and cumulative fuel consumption, engine speed, and engine load over any specified speed-time profile. The model was expanded by the Department of Transportation in the mid-1970's and the Environmental Protection Agency in the late 1970's to evaluate the effects of driving cycle changes on automobile fuel economy and emission levels.

The VEHSIM program was modified by an EPA contractor to perform simultaneous computations of emissions for HC, CO and NOx. This was accomplished by writing a new program, VSIME, which utilizes the VEHSIM program output for engine speed and torque time histories and engine emission maps as inputs to calculate instantaneous and cumulative emission rates over the driving cycle. The program output includes emission quantities computed by VSIME and fuel consumption quantities computed by VEHSIM.

Inputs to VEHSIM are organized into three categories:

- engine map for fuel consumption;
- driving cycle data; and
- vehicle configuration data.

The engine map is a matrix of fuel consumption rates and manifold vacuum levels across a range of possible engine speed and load points. For each discrete combination of speed (rpm) and load (in units of lb-ft) contained in the map, a fuel consumption rate (in pounds per hour) and manifold vacuum (in inches of mercury below atmospheric) is provided. Intermediate values are determined by an interpolation routine built into the model.

The driving cycle file specifies the vehicle speed for each "segment" of the cycle. Segments are nominally defined to be one second in length. Cycle specifications are available for a variety of driving cycles, including the LA4 driving cycle.

Vehicle configuration data characterize vehicle weight, frontal area, aerodynamic drag coefficient, rolling resistance, drivetrain efficiency, shift logic, fan losses, power steering losses, and air conditioning losses. The shift logic is expressed for gear changes based on vehicle speed and manifold vacuum.

For a selected vehicle configuration, VEHSIM computes the engine speed, load required to maintain the acceleration, and speed requirements set for each segment of the specified driving cycle. The instantaneous fuel consumption rate is determined by a double interpolation with respect to speed and load within the engine map. The first two interpolations are with respect to load within each of the relevant rpm settings. The second interpolation is between the load values for each of the rpm settings. The program employs a series of tests to determine whether a vehicle has achieved the velocity required by a particular segment. The length of the segment is extended as necessary in cases where the selected combination of vehicle configuration and engine lacks the power necessary to maintain the specified speed-time profile.

The outputs of VEHSIM include the following:

- cumulative distance (miles) and time (seconds);
- second-by-second and cumulative fuel consumption (pounds);
- second-by-second engine horsepower (hp) and torque (lb-ft);
- second-by-second engine speed (rpm); and
- second-by-second manifold vacuum (inches of mercury).

Inputs to VSIME consist of the above outputs from VEHSIM plus engine emission maps for HC, CO and NOx. Each engine emission map gives the emission rate as a function of engine rotational speed and engine torque (lb-ft). The HC and NOx emission rates are input in units of grams per hour. The CO emission rate is entered in units of 10 grams per hour.

For each segment of the driving cycle, the time duration is defined to be one second. VSIME reads the load and the rpm values computed by VEHSIM and uses that information to compute the instantaneous emission rate. As with the fuel consumption calculation within VEHSIM, emission rates are determined by double interpolation with respect to load and rpm within each engine map. The VSIME program predicts HC, CO, and NOx emissions for each second of the driving cycle. There are currently seven different 1970s vintage engine maps in the format required by the model; they span a size range from 91 to 350 cubic inches. For several of the engines, the emissions map is available for both "engine-out" and "tailpipe" emissions, after the exhaust passes through an oxidation catalyst. Maps for late-model engines equipped with 3-way catalysts are not yet incorporated in the model.

Currently, the model allows the user to select from seven different chassis ranging from 2500 to 5000 pounds; however, it is possible to add weight to these chassis through the user-selectible inputs. There are also several different transmissions from which to choose.

During 1987, the emissions-prediction version of the model was recreated by Sierra from a written description of the earlier EPA effort. (The original version of the model which predicts emissions has been lost by EPA.) Sierra's version of the model currently has over 4,000 lines of source code and comments. To distinguish Sierra's version of the model from the original, we call the emissions model "VEHSIME".

One limitation of the original version of VEHSIME is that it only uses data from warmed-up engines. As described in this report, a cold start and warm-up routine has now been added. The cold start routine was developed from second-by-second, pre-catalyst and after-catalyst modal emissions data on vehicles tested by EPA. With the cold start routine, the engine out emissions map is corrected based on the time since cold start. HC and CO emissions are increased by a factor of almost 2:1 at time zero. Stabilized engine out emissions are achieved at 450 seconds after cold start. The cold start routine also determines when to begin reducing the engine-out emissions by a catalyst efficiency factor (computed from the difference between the engine out and tailpipe emissions maps). Catalyst light-off is simulated at the point where the cumulative fuel consumption reaches the level of fuel that would be consumed during the first 2 minutes of operation on the LA4 cycle.

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