On-road Remote Sensing of Carbon Monoxide and Hydrocarbon Emissions During Several Vehicle Operating Conditions (Presentation)

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ABSTRACT

This study was designed to test the ability of a remote sensing device to measure the emissions of a vehicle under a variety of operating conditions. We measured emissions of an instrumented vehicle with driver-selectable air/fuel ratio to test remote sensors built by the University of Denver and General Motors Research Laboratories. We also measured the emissions of 23 other vehicles under a prescribed set of operating conditions. The results of these controlled tests indicate that the remote sensors measure carbon monoxide emissions within ±5% of the instrumented vehicle measurement, and measure hydrocarbon emissions within ±15% of the instrumented vehicle measurement. On repeated vehicle runs, the CO emissions were highest and showed the most variability during hard acceleration, and were lowest and showed the least variation during steady cruise of 15-45 mph. Hydrocarbon emissions were lowest and showed least variation during all accelerations, but were also repeatable during steady cruises. We did not test vehicles at speeds higher than 45 mph in this study.

INTRODUCTION

Two major elements of the California Air Resources Board's (ARB) motor vehicle emissions control program are stringent emission standards for new cars and proper maintenance of emission control equipment throughout the life of the vehicle. The emission standards for new vehicles have been reduced progressively since controls began in 1966, requiring automobile manufacturers to develop new technologies to meet the regulations. Further reductions in new car emission standards intended to achieve the state ambient air quality standards will take effect during the remainder of this and into the next decade. As a result, manufacturers will need to develop additional new technologies to reduce emissions. In addition, changes in the formulation of fuels will be required to help vehicle manufacturers meet these tough new emissions standards. In 1998, manufacturers will need to certify that a portion of their fleet (two percent) has zero emissions.

In order to retain the full benefits of progressively lower standards, the State requires vehicle owners to maintain emissions within established limits over the useful life of their vehicles by participating in a biennial inspection and maintenance program. This program, known as Smog Check, consists of a three-part inspection for all 1966 and newer model year non-diesel vehicles. First, the mechanic performs a visual inspection of required emission control equipment. Next, certain components are tested to verify that they are functioning properly. Finally, the vehicle is given a computerized tailpipe emissions test at low idle (~800 rpm) and, for 1981 and newer model year vehicles, at 2500 rpm. There are 27 different combinations of emissions standards for carbon monoxide (CO) and hydrocarbons (HC), depending on the model year and the emission control equipment installed.[1] An owner must repair the vehicle, subject to cost limits, if it fails any part of the Smog Check test. The cost limits range from $50 for the oldest vehicles to $300 for the newest. If the emission control equipment has been deliberately tampered with, the vehicle must be repaired prior to registration without regard to cost.

These approaches to regulating emissions from motor vehicles have been an effective means of reducing air pollution in California for the last 25 years. Despite the pressures of population growth and an increase in the number of vehicle miles travelled, air quality has improved in many areas of the state. However, studies funded by the Air Resources Board indicate that a minority of on-road vehicles emit a disproportionately large amount of exhaust emissions. Among newer vehicles, 80-90% produce far less than the allowable emissions; but, even for vehicles only one or two years old, high emitters are not uncommon.[2,3] If these high emitting vehicles could be identified and the effectiveness of their emission control systems restored, additional improvements in air quality could be realized.

In December 1989, the ARB, the South Coast Air Quality Management District (SCAQMD), and General Motors Research Laboratories (GMRL) jointly sponsored a study to investigate the reasons for persistent high carbon monoxide concentrations near Lynwood in the Los Angeles basin. As part of that study, we used a remote sensing instrument developed by the University of Denver (DU) to measure the CO emissions of the in-use fleet on surface streets and freeway ramps in the Lynwood area.[3,4] The device, called the FEAT (for Fuel Efficiency Automobile Test), was shown to accurately measure CO concentrations in double blind tests using a specially equipped GM vehicle. One conclusion from this study was that 10 percent of the in-use vehicle fleet was responsible for 55 percent of the CO emissions, on the basis of the investigators' measurement of the mass of CO emitted per gallon of fuel burned. In separate studies, DU and GMRL have reported similar results in other cities.[5,6]

The results of the previous studies showed sufficient promise that the ARB decided additional research was needed to investigate the use of remote sensing as a tool for measuring instantaneous emissions of in-use motor vehicles. Furthermore, both DU and GMRL added the capability to measure hydrocarbon emissions simultaneously with CO emissions. Also, Hughes Aircraft Company recently designed and built a prototype remote sensor based on a different measurement technique. The work described here is part of a comprehensive research project to investigate in-use emissions of motor vehicles using remote sensing. We tested the remote sensors built by DU, GMRL, and Hughes Aircraft Company in this study. The results from the Hughes device will not be reported here, however, since the instrument is still in early development.

The research plan for the larger, comprehensive project consisted of three major parts. In the first part, reported here, we tested the remote sensors in a controlled manner against each other and against an instrumented vehicle. We also tested a variety of vehicles under similar operating modes to establish the variability of emissions under modes likely to be encountered in the field. In the second part of the project, we used the remote sensor to identify high-emitting vehicles on a surface street. With the help of the California Highway Patrol, we stopped a number of these vehicles for further testing by a roadside inspection team and, for some vehicles, on a roadside dynamometer. The third part of the larger project consisted of measuring emissions at numerous locations both within and outside the Los Angeles basin to further document emissions of the vehicle fleet.

STUDY DESIGN

This part of the larger study had three main objectives: (1) to validate the remote sensor measurements, particularly for HC; (2) to compare measurements made by different remote sensors; and (3) to compare emissions of a variety of vehicles under a prescribed set of operating modes. To achieve the first objective, we measured emissions at steady cruise from an instrumented vehicle. We addressed the second objective by measuring emissions from the GM car using five remote sensors from three different research groups. To achieve the third objective, we tested 12 vehicles provided by ARB and 11 vehicles provided by Automotive Testing and Development Services, Inc. (ATDS), an automobile testing lab.

We used a specially-instrumented General Motors vehicle to test the accuracy and repeatability of the remote sensors. The vehicle, a 1989 Pontiac SSE with a 3.8 L "3800" 6-cylinder engine, carried two Horiba MEXA non-dispersive infrared analyzers to measure exhaust gas concentrations. One measured HC and CO, while the other measured CO and CO_2. A data logger digitized the signal from the analyzer and passed the results to an on-board Toshiba 3200 laptop computer. The computer was also interfaced to the "Assembly Line Data Link" (ALDL) to provide two-way communication between the laptop computer and the engine computer. With this link, we were able to vary the air/fuel ratio while driving, and also to obtain parameters such as vehicle speed and engine rpm from the engine computer. The laptop computer merged the data from the engine computer and the data logger, and could be triggered to print the results and store them on the hard disk. This arrangement provided us with an on-board data acquisition and analysis system to obtain near real-time (the system had an overall delay of 4 seconds) analysis of exhaust emissions.

All measurements involving the GM instrumented car were made with the car cruising at about 30 mph. After selecting an air/fuel ratio on the computer, the driver accelerated to 30 mph, then set the cruise control. We took this precaution to ensure that all remote sensors were exposed to exhaust emissions that were as uniform as possible. As the car passed the first sensor, the driver activated a print program to record emissions throughout the test course. The results of these test runs provided data for the first two objectives of this study.

We compared the measurements of four remote sensors in this study. Three sensors were FEATs, designed and built by the University of Denver.[7] The fourth one was designed and built by General Motors Research Laboratories.[6] Both the FEAT and the GMRL sensors are non-dispersive infrared absorption instruments. A beam of infrared radiation is directed across a single line of traffic at a detector on the other side. The detector splits the beam into four wavelength channels for CO, CO_2, HC, and reference. The remote sensors measure the plume concentrations of CO, CO_2, and HC in the dispersing exhaust, then compute the plume CO/CO_2 and HC/CO_2 ratios by regressing the CO and HC against CO_2. The CO, CO_2, and HC exhaust concentrations are computed from the ratios. The FEAT data reduction algorithm will reject a measurement if the regression uncertainty exceeds a threshold. For CO, the standard error of the measurement must be less than 20% of the mean for CO>1%, or greater than 0.2% (absolute) for CO of one percent or less. For HC, the standard error must be less than 20% of the mean for HC>0.375% (as propane), or less than 0.075% (propane) for HC of 0.375% or less. The General Motors instrument did not have this feature.

We calibrated all the sensors, including the on-board Horiba instruments, with one of a variety of known mixtures of propane, CO, and CO_2. Each of us used a mixture appropriate for our own sensor, and we each measured all of the calibration gases to obtain a cross-comparison. We applied a factor of 0.5 to convert the propane measurements to hexane equivalent (this conversion factor may, in fact, differ slightly for each remote sensor).

To examine the variability of vehicles under different operating modes, we tested 23 vehicles provided by ARB and ATDS. One of the ARB vehicles was methanol-fueled (M85), and one was a flexible-fueled vehicle (running on gasoline). The other ARB vehicles were part of an ongoing study of the effectiveness of California's inspection and maintenance program. No information was available on the type of fuel used in these other vehicles, except that they all used gasoline. These vehicles all received Smog Check inspections within a few days of this study, and all received Federal Test Procedure (FTP) dynamometer tests at ARB's Haagen-Smit Laboratory. All of the vehicles from ATDS were gasoline powered. Some vehicles from ATDS were tested with and without a catalytic converter. All but two of the ATDS vehicles had been tested on a dynamometer using the FTP. Finally, we tested three 1991 model year rental cars on a series of acceleration runs.

A trained driver from ATDS drove each of the cars provided by ATDS and ARB. The test procedure consisted of 10 passes through the test course under different operating modes. The parking lot had a very slight slope, so we repeated the set in each direction. We tested most cars twice in this manner, but some were tested a total of four times. The 10 passes included rolling idle (car in gear but foot off the accelerator); steady cruise at 5, 15, 30, and 45 mph; light, medium, and hard acceleration; and two passes decelerating from 30 mph. We tried to make the two deceleration passes similar to each other. We used a radar gun to measure speed and acceleration as the car passed one or two FEAT units.

We conducted the study from May 21-23, 1991 in an empty parking lot at the Santa Anita Race Track in Arcadia, California. The weather on these days was typical for southern California. Ozone peaked at 18 pphm on May 23 at Glendora. On the first day, we set up all five sensors side-by-side with a distance of 39 feet separating the first and last sensors. Most of the runs conducted on the first day involved the instrumented GM car, although several runs were made with test vehicles. On May 22 and 23, we separated the sensors by a total distance of approximately 200 feet. We placed a FEAT at each end of the test course, with another FEAT and the GM sensor side-by-side near the middle of the test course. These two sensors were separated by 11 feet. FEAT 3004 was located on the west end, FEAT 3002 was in the middle, and FEAT 3005 was at the east end of the test run. We made most runs on May 22 and 23 with test vehicles. General Motors ran the instrumented car on several runs on May 22, but did not use it on May 23.

RESULTS

The results of this study will be presented in three parts corresponding to the main objectives. Figure 1 plots the CO and HC measurements for each remote sensor against the GM On-Board (GMOB) measurements. The FEATs and the GM remote sensor (GMRS) compared very well to the GMOB CO measurements. The HC measurements exhibited more scatter than the CO measurements for all three remote sensors. These analyses show that the FEAT and GMRS devices accurately measure the instantaneous emissions of CO and HC.

We were able to achieve a wide range of on-board CO emissions (zero to ten percent) by varying the air/fuel ratio on the GM vehicle. The HC emissions, however, could not be increased enough to be comparable to many high emitters we have observed on the road, even after we induced a misfire by disconnecting an ignition wire. For example, the highest emissions we measured from the GM vehicle were less than 0.2% hexane. In the high-emitter part of this project, over 55 of 337 vehicles (16%) pulled over for further testing emitted more than 0.2% hexane. Of all 60,000 vehicles measured, nearly 5,000 (8%) were observed emitting over 0.2% hexane. Although the remote sensor HC measurements correlate at a lower level than the CO measurements, some of the scatter evident in the HC measurements may be due to the generally low HC emissions. Despite the scatter, the remote sensors measure HC within ±15% of the calibrated, on-board measurement. The remote sensors measure CO within ±5% of the on-board measurement. These accuracies are derived from the slope of the regression lines.

Figure 2 shows all the remote sensors plotted against FEAT 3002. The three FEATS and the GMRS compared quite well to one another for CO, but again the HC comparisons exhibited more scatter. FEAT 3005 did not measure hydrocarbons as well as the other two FEATs, as indicated by its r^2 of 0.76 and its coefficient of 1.88 compared to FEAT 3002. Just prior to the start of this study, FEAT 3005 lost the mirror that focuses the IR beam on the HC detector. We repaired it temporarily, but there was insufficient time to align it properly, which may have resulted in poorer HC data quality for this sensor.

The third objective of the study was to test a variety of vehicles under a prescribed set of operating modes. We tested most of the 23 vehicles at least twice. Overall, we analyzed a total of 50 test runs. We obtained measurements for 10 passes for each test run. For this analysis, we will present only the results from FEAT 3002, located at the center of the test array.

Figure 3 shows a box and whisker plot of all CO and HC measurements from the 23 vehicles as a function of operating mode. This diagram shows the distribution of emissions of the set of vehicles measured. The box represents the 20th and 80th percentile groupings, and the bar within the box represents the median measurement. In most instances, the exhaust CO concentrations showed the least variability between different vehicles at cruising speeds of 15-45 mph, and for light acceleration. There were only a few high emitters when the vehicles operated at 45 mph and under light acceleration. The greatest variation and highest median exhaust concentrations of CO occurred under hard acceleration. The medium acceleration showed variations between vehicles similar to 5 mph cruise. The idle pass and the two deceleration passes were comparable for CO emissions. The HC measurements showed the least variability between different vehicles during accelerations. The greatest variation between vehicles and the highest median exhaust concentrations of HC occurred during decelerations. At cruising speeds, the 15 mph and 30 mph passes showed the least variation. The idle, 5 mph and 45 mph passes showed slightly higher variability.

We measured the emissions of most vehicles at least two times. Figure 4 shows how consistent the emissions of the same vehicle were for different runs. The diagram shows the distribution of the difference between the highest and lowest emissions of each vehicle for each operating mode. For CO, the repeat emissions were within one percent CO for more than 80 percent of the vehicles measured for all operating modes except hard acceleration. For HC, the repeat emissions were within 0.25% hydrocarbon for over 80 percent of the vehicles in all cases except deceleration. The acceleration emissions were remarkably consistent for HC, with nearly all repeat emissions within 0.1% HC, measured as hexane. For steady cruise of 15-45 mph, a few vehicles ranged up to 0.7% hexane between measurements. We refer to these vehicles as "flippers", because they flip between high and low emissions. A few vehicles were "flippers" for CO also (not necessarily the same vehicles as for HC).

We tested two ARB vehicles, a 1982 Nissan Stanza and a 1979 Cadillac, four times each, twice on May 22 and twice on May 23. In the interim, the Cadillac had a Smog Check and an ignition timing adjustment. The Nissan had no adjustment between the two sets of tests. Tables I-IV show the individual CO and HC measurements from each pass for these two vehicles, as well as the mean and standard deviation of the readings for each operating mode. The tables show all reported measurements, including reported zero values and negative numbers. The negative numbers are all within the measurement uncertainty of the instrument, and are retained in the data set so as not to bias the means. The Nissan appears to be a "flipper" for CO at medium acceleration. On May 22, the emissions averaged 4.1% CO, while on May 23, they averaged 1.5% CO. For the other vehicle operating modes, the differences from one run to the next are insignificant. The emissions for the Cadillac were consistent for all four runs, even though it had a Smog Check and a timing adjustment between the first two and the last two runs.

All the vehicles tested in this part of the study were clean compared to the vehicles pulled over for inspections in the high-emitter part conducted later on. Only under conditions of hard accelerations ("foot to the floor") did emissions of some vehicles approach the cut point we applied in the high-emitter part of the study.

CONCLUSIONS

We have demonstrated in a blind experiment that remote sensing instruments built by the University of Denver and by General Motors Research Laboratories accurately measure carbon monoxide exhaust emissions within ±5% and hydrocarbon exhaust emissions within ±15%. Both remote sensors exhibit high correlations ($r^2 > 0.98$ for CO, $r^2 > 0.85$ for HC) with on-board measurements of emissions made by General Motors Research Laboratories, and correlate highly with each other ($r^2 \sim 0.99$ for CO, $r^2 \sim 0.85$ for HC).

We have also shown how the operating modes of a small fleet of relatively clean vehicles can affect their on-road emissions. Exhaust carbon monoxide concentrations showed the least variation between different vehicles and the lowest median concentrations during 15-45 mph cruise modes and for light acceleration. The greatest variation of exhaust CO emissions between different vehicles and the highest concentrations occurred during hard accelerations. Exhaust hydrocarbon measurements showed the least variation between different vehicles and the lowest average concentrations during accelerations. The greatest variation between different vehicles and the highest average concentrations occurred during decelerations. The cruise passes at 15 and 30 mph were the most consistent of the cruise patterns tested.

On-road exhaust carbon monoxide emissions for the same vehicle on different runs were within 1% CO of one another for over 80 percent of the vehicles tested for all operating modes except hard acceleration. On-road exhaust hydrocarbon emissions were within 0.1% HC of one another for different runs for over 80 percent of the vehicles tested during 15-45 mph cruise and all accelerations. For very slow cruise and deceleration, the exhaust HC emissions ranged over a wider span for repeated tests.

Based on this analysis, we have determined that steady cruise at 15-45 mph (typical surface street speeds), and light to medium accelerations produce stable emissions of exhaust CO and HC. These modes are most favorable for using the DU and GMRL remote sensors. The study did not address speeds in excess of 45 mph, however. Highway-speed cruises of 55-65 mph may also produce stable emissions and may be as favorable as 15-45 mph cruises. Modes of hard acceleration, deceleration, and very slow (0-5 mph) cruise do not yield such stable, reproducible emissions of exhaust CO or HC. Furthermore, the relatively clean vehicles in this study averaged higher CO emissions only during hard accelerations and higher HC emissions only during decelerations and very slow cruise. Note that vehicles that are high emitters during conditions of moderate cruise or light acceleration are likely to be high emitters during any type of emissions test.

ACKNOWLEDGMENTS

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DISCLAIMER

The contents of this paper report the authors' findings and do not necessarily reflect the views and policies of the California Air Resources Board. The mention of contractors and commercial products is not to be construed as either an actual or implied endorsement of such individuals or products.

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Table I. Percent CO Emissions for 1982 Nissan Stanza.

	Idle	5 mph	15 mph	30 mph	45 mph	Lt Acc	Md Acc	Hd Acc	Decel 1	Decel 2
5/22 12:00	2.8	2.2	0.4	0.4	0.2	1.5	4.1	9.5	2.1	7.3
5/22 12:15	3.7	3.3	1.3	0.0	0.1	1.4	4.2	5.8	3.3	3.4
5/23 10:50	2.0	1.7	0.0	0.0		0.1	1.5	7.9	2.5	2.6
5/23 11:10	3.7	2.4	0.9	1.3	0.8	0.2	1.5	7.5	2.9	3.4
Mean	3.1	2.5	0.7	0.4	0.4	0.6	2.4	7.1	2.9	3.1
Std Dev.	0.7	0.6	0.5	0.5	0.3	0.7	1.3	1.3	0.4	1.9

Table II. Percent CO Emissions for 1979 Cadillac.

	Idle	5 mph	15 mph	30 mph	45 mph	Lt Acc	Md Acc	Hd Acc	Decel 1	Decel 2
5/22 12:30	0.3	0.3	0.3	0.8	0.3	0.1	0.1	4.4	0.4	0.4
5/22 12:45	0.2	0.3	0.3	0.7	0.3	0.2	0.1	4.0	0.4	0.5
5/23 12:45	0.9	0.3	0.2	0.8	0.7	0.3	0.6	4.6	0.4	2.6
5/23 1:00	0.3	0.2	0.1	0.5	0.6	0.4	0.1	5.0	0.3	0.2
Mean	0.5	0.2	0.2	0.7	0.5	0.3	0.3	4.5	0.4	1.1
Std Dev.	0.3	0.1	0.1	0.1	0.2	0.1	0.2	0.4	0.1	1.0

Table III. Percent HC Emissions for 1982 Nissan Stanza.

	Idle	5 mph	15 mph	30 mph	45 mph	Lt Acc	Md Acc	Hd Acc	Decel 1	Decel 2
5/22 12:00	0.056	0.059	0.045	-0.022	-0.006	0.027	0.048	0.081		0.24
5/22 12:15	0.064	0.064	0.040	0.087	0.14	0.014	0.033	0.045	0.14	0.12
5/23 10:50	0.046	0.080	0.046	0.015		0.022	0.022	0.065	0.097	0.073
5/23 11:10	0.072	0.066	0.049	0.069	0.025	0.013	0.027	0.057	0.11	0.092
Mean	0.061	0.070	0.045	0.057	0.081	0.016	0.027	0.056	0.11	0.094
Std Dev.	0.010	0.008	0.003	0.043	0.061	0.006	0.010	0.013	0.018	0.063

Table IV. Percent HC Emissions for 1979 Cadillac.

	Idle	5 mph	15 mph	30 mph	45 mph	Lt Acc	Md Acc	Hd Acc	Decel 1	Decel 2
5/22 12:30	0.037	0.016	0.031	0.039	0.031	0.016	0.023	0.036	0.040	0.042
5/22 12:45	0.026	0.030	0.028	0.028	0.030	0.005	0.007	0.022	0.032	0.039
5/23 12:45	0.023	0.011	0.017	0.021	0.001	0.014	0.016	0.055	0.047	0.089
5/23 1:00	0.024	0.010	-0.018	0.025	0.023	0.029	-0.001	0.023	0.037	0.025
Mean	0.024	0.017	0.009	0.025	0.018	0.016	0.008	0.033	0.039	0.051
Std Dev.	0.006	0.008	0.020	0.007	0.012	0.008	0.009	0.013	0.005	0.024

Figure Captions

1. Comparison of Remote Sensor Measurements to On-Board Measurements of Carbon Monoxide and Hydrocarbon. The regression line and regression model statistics are shown for each figure. The remote sensors accurately measure CO within ±5% when compared to the calibrated, on-board measurements, and accurately measure HC within ±15%.

2. Comparison of Remote Sensors to Each Other. The CO measurements of all remote sensors compared very well to one another. FEAT 3005 had a misaligned mirror that affected its hydrocarbon measurement, and there is a bias between the FEAT and the GM remote sensor for hydrocarbon.

3. Differences Between Emissions of 23 Vehicles According to Vehicle Operating Mode. This shows the distribution of emissions of different vehicles for a variety of operating modes. The box includes 60 percent of the data, while the whiskers show the range. The horizontal bar within the box denotes the median, and the notch includes the 95% confidence interval for the median.

4. Range of Repeat Measurements of Emissions of 23 Vehicles According to Vehicle Operating Mode. This shows the variability of emissions of a single vehicle measured multiple times. The box includes 60 percent of the data, with the highest and lowest 20 percent shown as individual data points. Most of the measurements are repeatable, although a few "flippers" are evident. The "flippers" emit low amounts on some passes and high amounts on others. Most data points are the spread between two measurements. A few are the spread of three or four runs on the same vehicle.

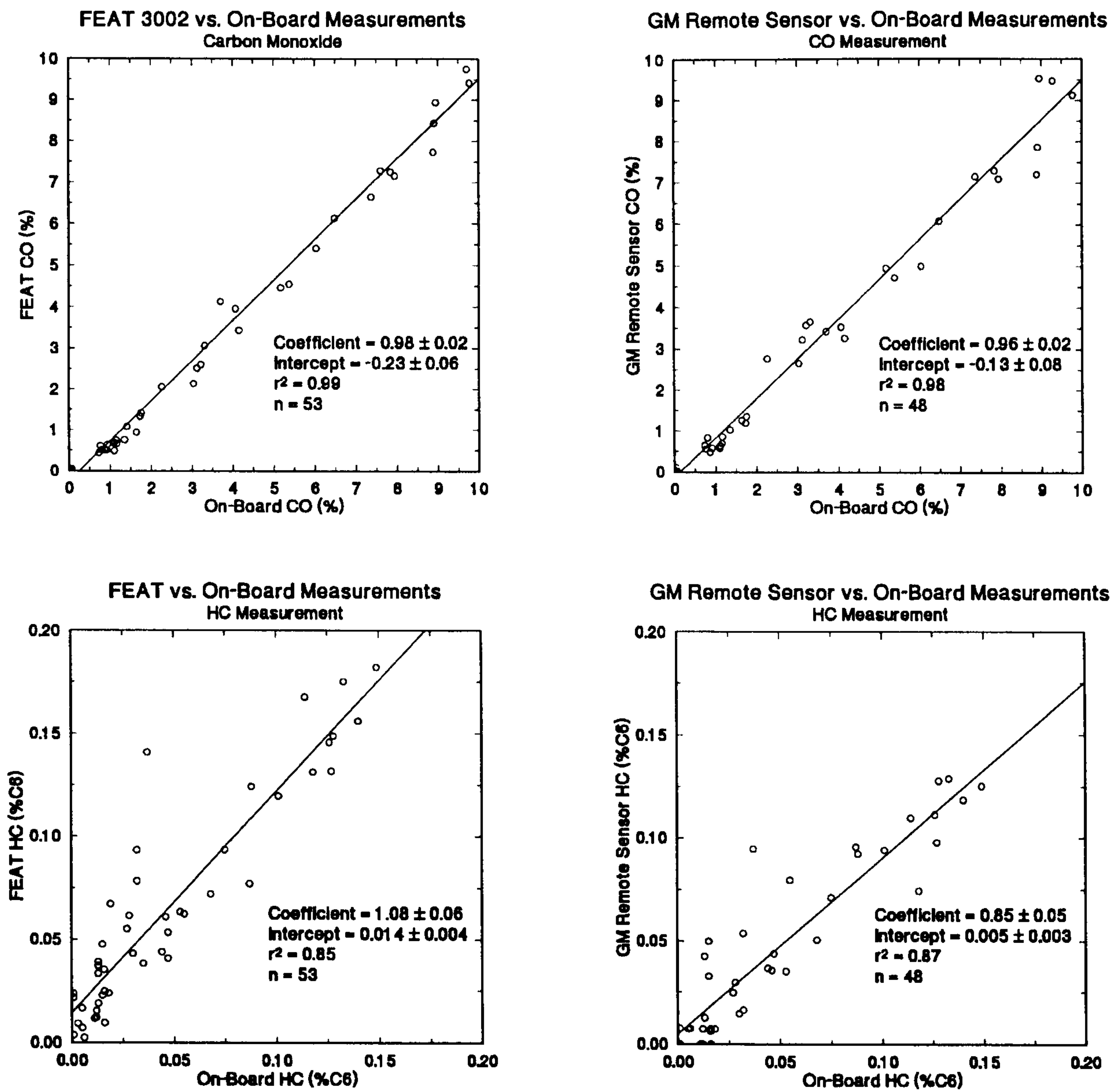


Figure 1. Comparison of Remote Sensor Measurements to On-Board Measurements of Carbon Monoxide and Hydrocarbon.

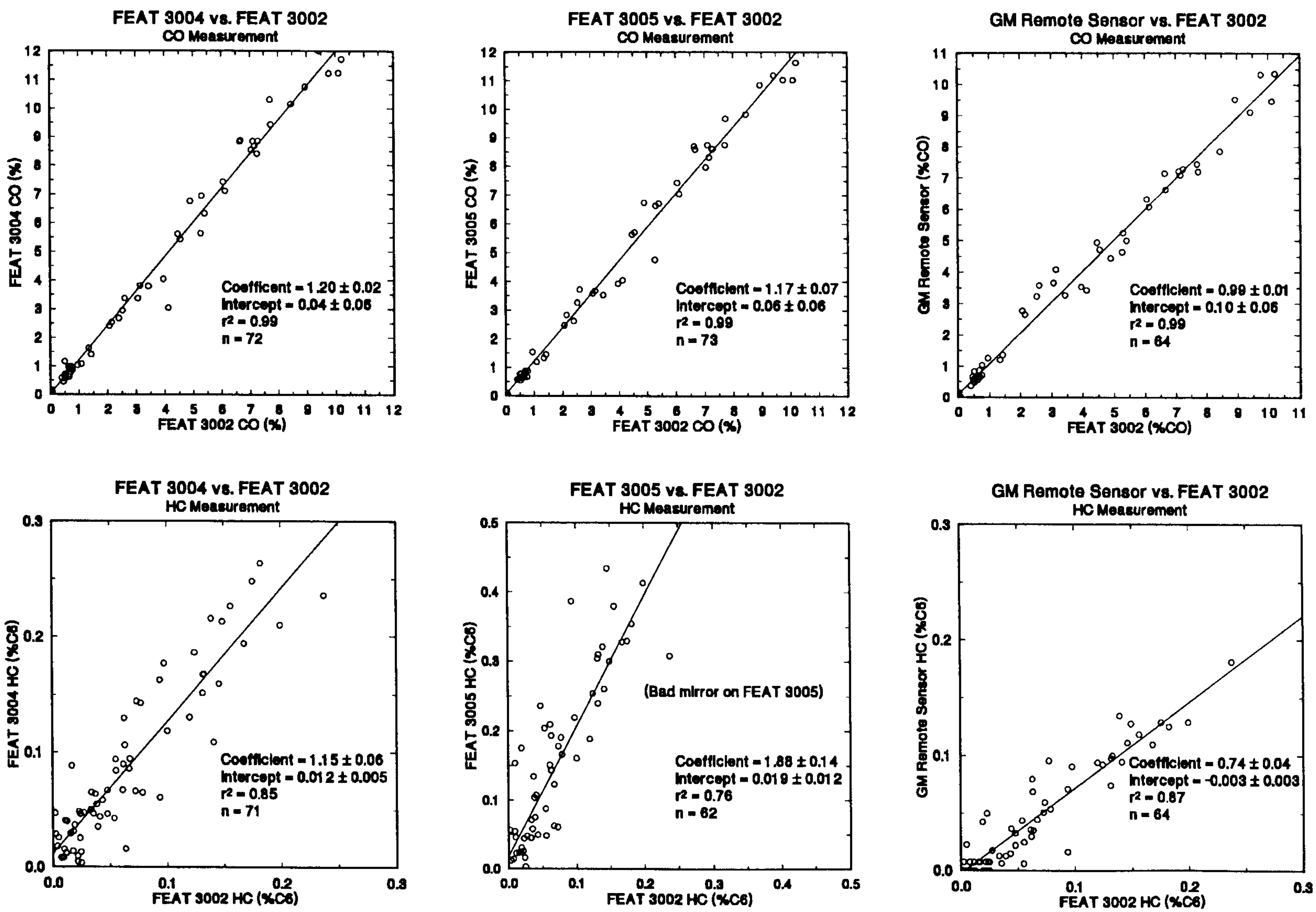
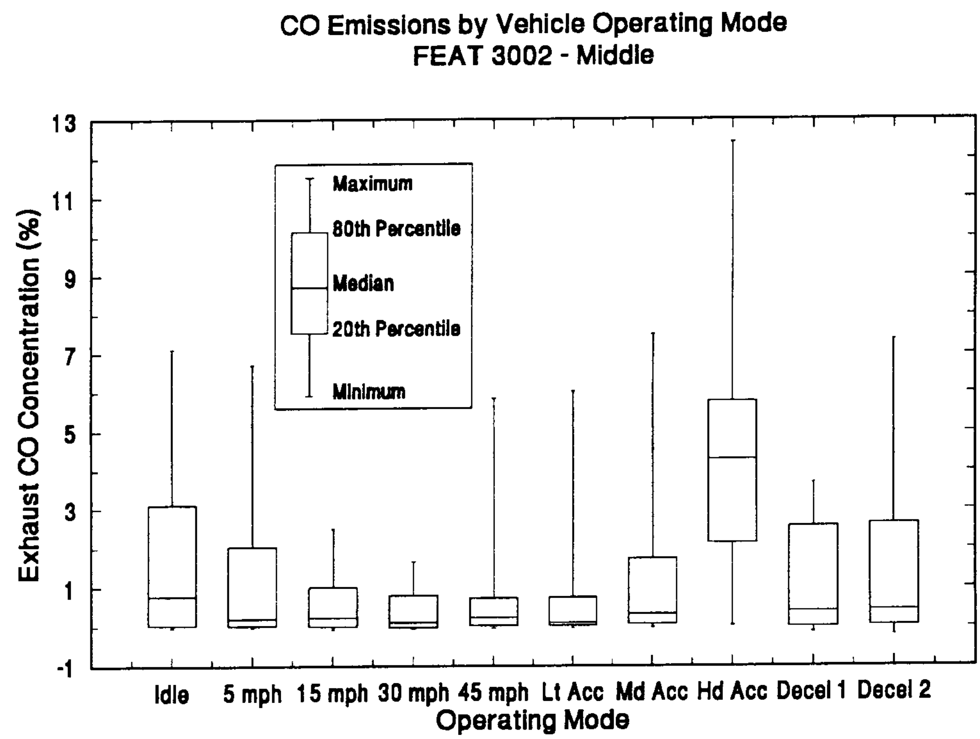


Figure 2. Comparison of Remote Sensors to one another.



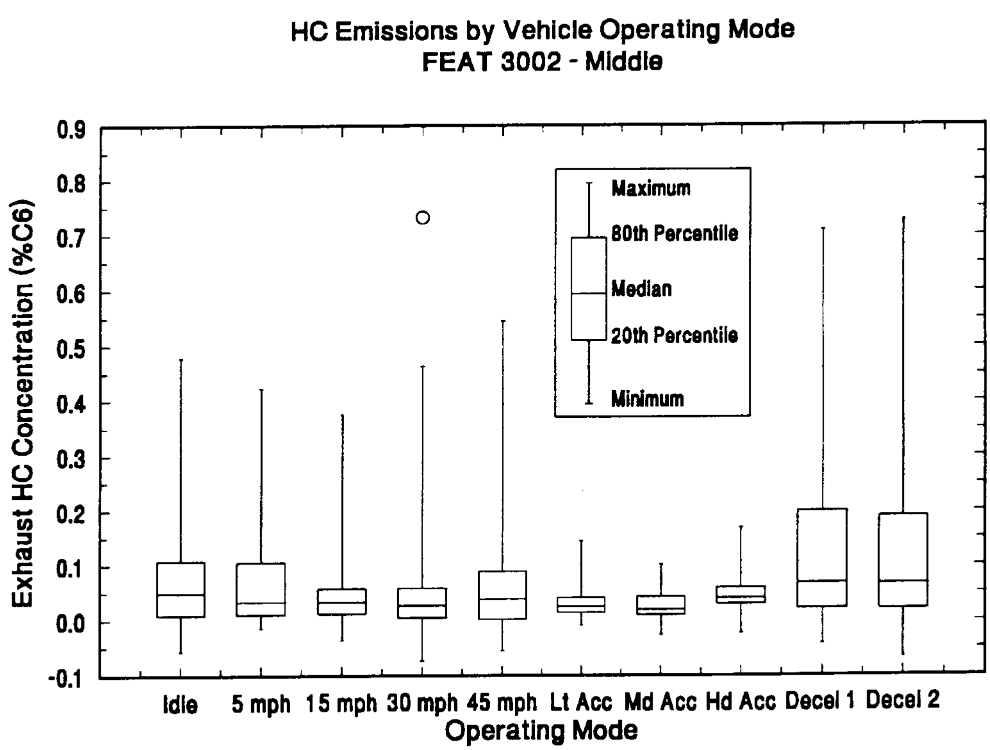
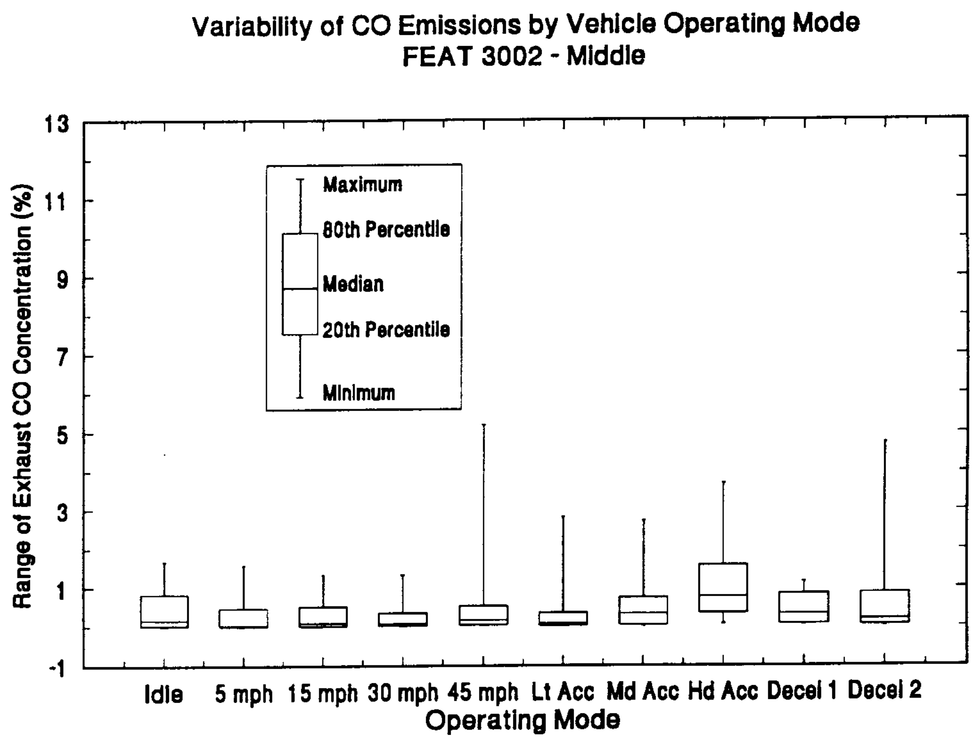


Figure 3. Differences Between Emissions of 23 Vehicles According to Vehicle Operating Mode.



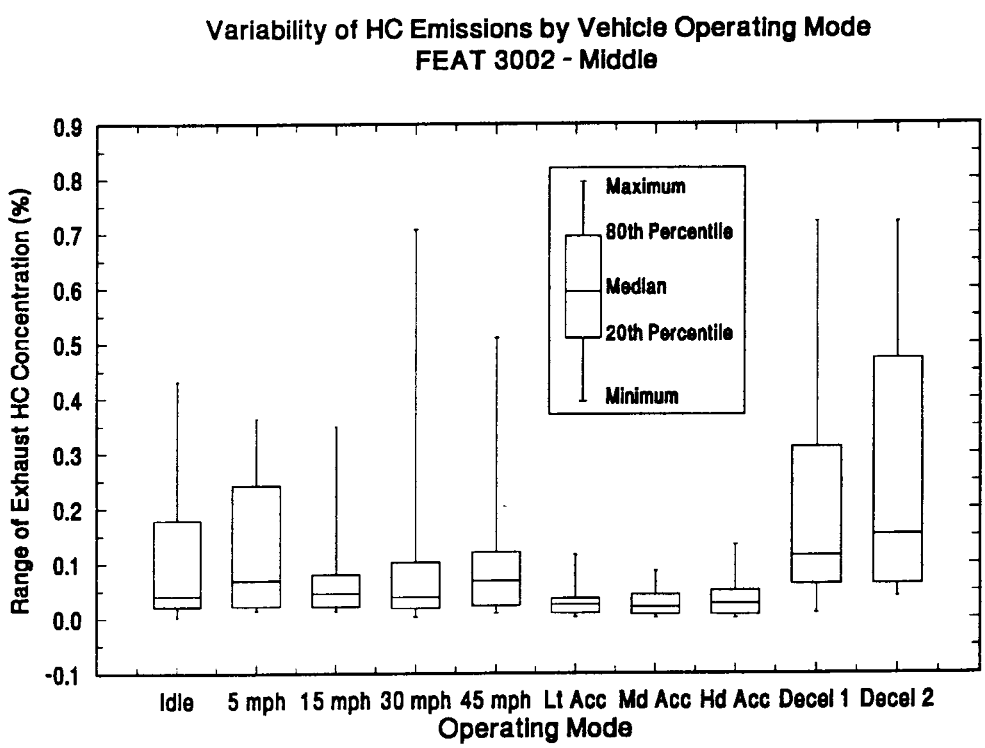


Figure 4. Range of Emissions on Repeated Runs of 23 Vehicles According to Vehicle Operating Mode.