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INTRODUCTION

The NO remote sensor was built as an additional channel to the FEAT system in unit FEAT 3006. It was used on several occasions in El Paso Texas and in Juarez Mexico. Drive-by comparisons of the sensor with a fully instrumented Ford Taurus (with computer controlled engine override, four gas analyzer (MPSI), a UV based NO exhaust analyzer and functional catalyst), were undertaken at several on-road sites during the El Paso and Juarez Studies. In addition, drive-bys under more controllable conditions were conducted in the hotel parking lot in El Paso. These initial studies were helpful in evaluating the performance of the NO remote sensor. A more complete study specifically designed to validate the sensor's performance was conducted at the Ford Motor Company Dearborn Proving Ground in Michigan, where the NO emissions measured by the FEAT 3006 unit (modified for the simultaneous analysis of CO, HC, NO, and CO_2) were compared with real-time NO emissions measurements from on-board instrumentation in two instrumented vehicles. The two vehicles were: a Ford Aerostar with an on-board instrumentation developed by Ford Research, and a Ford owned Taurus with on-board instrumentation developed by Denver Research Institute (mentioned above).

The Aerostar contains an on-board FTIR , an on-board air/fuel sensor , and an on-board computer system. The FTIR is capable of acquiring time-resolved emissions of thirty exhaust components including CO, CO_2, and NO. The on-board computer system controls engine air-to-fuel ratios in open and closed loop modes, and measures and monitors numerous engine operating parameters. These engine parameters, when combined with the emission data from the FTIR, provide a comprehensive and accurate account of the vehicle emissions and the conditions which produced them.

The Taurus is equipped with on-board monitors for CO, CO_2, HC, oxygen, and a newly developed fast response on-board NO system. The Taurus has the ability to operate in an open or closed-loop mode with or without EGR. These modes can be changed in a few seconds by the driver, and the Taurus is capable of operating at any pre-set air-to-fuel ratio with or without EGR.

Altering the engine operating parameters provided a wide range of fairly reproducible NOx emissions which facilitated this study. The Taurus NO emissions ranged from ~50 ppm to as high as 5500 ppm. Typically, NO emissions were less than ~450 ppm in closed loop operation with EGR activated, and in rich operation. On the other extreme, NO emission levels consistently greater than 2000 ppm and as high as 5500 ppm were achieved under stoichiometric or slightly lean conditions with the EGR disabled. Since the Aerostar was a California calibration vehicle equipped with a blank catalyst assembly and no EGR, its NO emission range was much narrower. The Aerostar NO levels never fell below ~750 ppm and never exceeded 3000 ppm.

The Dearborn Proving Ground study was designed to encompass this wide range of NO emissions. During the study, both vehicles were repeatedly driven past the FEAT system, under a variety of conditions. Usually, the vehicles were operated in a specific gear, at a given speed in either a cruise (steady state) or a slight acceleration driving mode. These modes were repeated at various gear, speed and air-to-fuel ratio settings.

EXPERIMENTAL

NO FEAT SYSTEM

The NO prototype system was calibrated in the same way as all FEAT systems (U.S Patent 5,210,702), by blowing a small puff of gas from a calibration cylinder with known CO, CO_2, propane and NO content in such a manner as to simulate the exhaust of a passing vehicle.

AEROSTAR TEST VEHICLE

A detailed description of the Aerostar test vehicle and associated on-board equipment is given in CRC VE-11-1 Final Report. For completeness the following abbreviated description is included.

The On-Board Emissions (OBE) vehicle is a 1992 stretch Aerostar minivan with a 3.0 L engine, calibrated for operation in California, and a 4-speed overdrive automatic transmission. The vehicle has been driven approximately 4000 miles prior to this program. For the purposes of the intercomparison study, the stock catalyst was then replaced with a blank catalyst which allowed the production of higher than normal exhaust emissions.

Aerostar On-Board Instrumentation

The OBE analysis system is comprised of several basic subsystems; 1) A Multicomponent Exhaust Gas Measurement System, 2) the OBE Power System, and 3) the Vehicle Data Acquisition System and Research Console (VDAS/RCON). Simplified block diagrams are given in Figures 1 and 2.

1. Multicomponent Exhaust Gas Measurement System

The Multicomponent Exhaust Gas Measurement System consists of three major components: a) the FTIR spectrometer and associated support hardware, b) the FTIR data acquisition system and software, and c) the exhaust gas sampling and dilution system (U.S. Patent 4,801,805, U.S. Patent 4,928,015, U.S. Patent 5,138,163).

a. The FTIR Spectrometer and Associated Support Hardware

The high resolution FTIR spectrometer (Nova-Cygni Model 120, Mattson Instruments, Inc., Madison, WI) is equipped with a water cooled glow bar source and a MCT detector. A variable path, multi-pass gas cell (Wilks, 20 Meter, Model 9020) with potassium bromide windows is used exclusively at the 14th order setting (21.75 meters) to improve the sensitivity of the system for all chemical species.

When the OBE is mobile, the nitrogen gas used to purge the spectrometer and the water used to cool the IR source are contained "on-board". The water for cooling the IR source is maintained below ambient temperature, and is recirculated from a insulated container using a submersible pump. The nitrogen gas for purging the FTIR is generated by boiling liquid nitrogen. An electric heater is placed in a 25 liter dewar of liquid N_2 and a pressure actuated switch maintains the gas pressure at 7-8 PSIG, while suitable valves and stainless steel tubing deliver the N_2 gas to the FTIR.

b. FTIR Data Acquisition System

Acquisition and processing of FTIR data are controlled by a PC compatible computer (Industrial Portable Personal Computer (IPPC) by Texas Microsystems) equipped with an Intel I860 based coprocessor board (CSPI Supercard AT). The data acquisition and processing routines were developed and patented by the Ford Motor Company Research Laboratories and licensed to Pierburg, GMBH. This software was designed for the specific purpose of (but not limited to) analyzing multi-component gas phase samples composed of chemical species typically found in dilute vehicle exhaust. The system can be used to acquire either time-resolved (every three seconds) or signal-averaged data. The hardware and software used with the system are capable of monitoring up to 50 individual components. During this study, data is acquired on 21 components. A listing of the species monitored by the FTIR system and their detection limits are listed in Table 1. With the current operating mode, the system provides no real-time emissions information to the driver.

c. Exhaust Gas Sampling and Dilution System

The Exhaust Gas Sampling and Dilution System is comprised of the heated sample line and a heated sampling and dilution system. A schematic diagram of the system is presented in Figure 3. As depicted, the sampling of raw vehicle exhaust is achieved by transporting a portion of the exhaust from the tailpipe, through the heated sample line, to a dilution chamber where the exhaust is mixed with a constant flow of N_2(g). A heated sample pump, positioned downstream of a self-regulating heated sample line, is used to draw a sample of raw vehicle exhaust from the sampling port to the dilution chamber. The sampling line was inserted into the tailpipe of the vehicle just past the catalytic converters. To prevent the condensation of water in the raw exhaust, the heated sample line, pump and dilution chamber are maintained at a temperature above the dew point of the raw exhaust sample (>68°C). Approximately 3 liters per minute of raw exhaust is extracted from the tailpipe. A portion of this sample (~2/3) is directed into the dilution chamber. The remainder of the sample is vented from the chamber. The sample remaining in the chamber is diluted, ~10:1, with $N_2(g)$. The $N_2(g)$ is supplied by the same $N_2(g)$ source used for purging the FTIR. A mass flow controller regulates the flow of $N_2(g)$ and hence the dilution ratio. The diluted sample is directed out of the chamber through a filter and into the gas cell via a pump downstream of the FTIR. Both the excess raw exhaust from the dilution chamber and the diluted exhaust are vented to the exterior of the vehicle.

2. Vehicle Data Acquisition System and Research Console (VDAS/RCON)

The task of acquiring vehicle data as well as controlling, and altering engine/powertrain calibration is accomplished using a software/hardware system referred to as the VDAS/RCON. This is a Ford proprietary PC based system that utilizes a shared memory approach to control vehicle operation and calibration. The VDAS/RCON can also acquire data from the powertrain controller as well as from external sensors and/or signal sources. These external inputs include air/fuel instrument signals, thermocouple signals, pressure sensors, and external triggers. Through the use of triggers and coordinated sampling techniques, data from multiple systems can be synchronized and overlaid for analysis. These capabilities are necessary when time based data correlation is required. Running under current versions of MS-DOS, all VDAS data files can then be analyzed using commercially available spreadsheet, statistical, graphical packages, or by its own built in analysis tools.

The vehicle instrumentation was shown above in Figures 1 and 2. The hardware consists of several components: 1) the Electronic Engine Controller (EEC) of the vehicle, which is the standard vehicle computer responsible for controlling the engine and emissions system; 2) the VDAS/RCON (described above); and 3) an 80386SX/16MHz microprocessor-based computer (GRiD Model 1755) which controls the RCON through a serial local network. In addition, external sensors were added to the exhaust system of the vehicle. A laboratory grade air/fuel sensor (Horiba Model MEXA-101λ) was installed adjacent to the factory HEGO sensor in the exhaust pipe. Two thermocouples, one prior to and one in the mid-bed of the first catalyst, monitor the exhaust system temperature. A list of the vehicle and engine operating parameters monitored by the system is shown in Table 2. All VDAS/RCON accessed signals are recorded at 1 second intervals.

3. The OBE Power System

There are 3 separate power systems on-board the vehicle, 110 VAC, 12 VDC and 48 VDC. The 110 VAC system supplies power for the FTIR, the mass flow controller for the dilution system, and the temperature controller used for the sampling system heater and the heated sample line. This power is supplied by a 1 KVA, 24 VDC to 120 VAC inverter (Nova Electric, Model 1K 60-24). The 24 VDC is provided by a pair of 130 AH, 12 VDC deep cycle batteries wired in series. The operating time using fully charged batteries is 3 hours.

There are 2 separate 12 VDC systems used on the vehicle. One is connected to the vehicle battery/alternator and the other is separate. The RCON, IPPC and the GRiD computers are connected directly to the vehicle battery and draw at total of 20 amps. The other 12 volt system supplies power for the submersible cooling pump for the FTIR source, the heater used to generate N_2(g) for dilution and purging the FTIR, the FTIR flow pump, the sample pump and its heater, and the sampling system heater. The on board batteries provide power for data collection for at least 3 hours.

TAURUS TEST VEHICLE

The Taurus test vehicle is a 1991 wagon equipped with a 3.8 liter PFI V-6 engine and automatic transmission. Both feedback and adaptive control systems are employed in the normal operating modes. The emissions control system uses dual oxygen sensors and catalysts in conjunction with a vacuum/electronic EGR. The Taurus is also equipped with a VDAS/RCON system (as shown in Figure 1). For the purposes of evaluating the FEAT NOx channel the air-to-fuel ratios in the Taurus were altered using the VDAS/RCON and locked in at values ranging from 0.95 to 1.1 with/without EGR. Signal information is recorded in raw data and calculated ppm formats, along with vehicle operating parameters, in a comprehensive data acquisition system.

Taurus On-Board Instrumentation

Exhaust gas sampling is conducted by two separate tailpipe probes of equal length, one for the NO detector and one for the four-gas analyzer. Figure 4 shows a schematic diagram of the set-up used for the two analysis systems. This method was selected to provide the best possible compromise between ease of use, system isolation, and instrument flexibility. Another consideration was the isolation of the newly developed NO analyzer and dilution pump system to minimize any potential negative interactions that may develop during its initial development. In order to prevent condensation in the UV analyzer cell, the raw exhaust was diluted with approximately 10 parts ambient air before flowing through the UV cell. This sufficiently lowers the dew point of the exhaust without trapping water and risking losses of soluble oxides of nitrogen. In this configuration, fast response times, on the order of 1.1 seconds were maintained. As an added precaution, small heater elements were placed around the lens assemblies to further insure against condensation.

The measurements of CO, HC, O_2, and CO_2 were conducted using an IR based "in flight" analyzer manufactured by MPSI. This unit was linked to a dedicated PC that was time correlated with the vehicle VDAS/RCON system. Slight difficulties were encountered with condensation during long data runs, however this did not affect test integrity as a periodic flush/purge procedure eliminated excess condensed moisture. The entire on-board system was powered from the vehicle battery and alternator.

ON-ROAD TESTS

There was a three day intercomparison study conducted at the Ford Dearborn Test Track. During this study the two test vehicles were driven past the remote sensor, while varying engine operating conditions and subsequently the NOx emission levels. The test conditions included varied vehicle speed (either steady-state or slight acceleration driving conditions), transmission gear, air-to-fuel ratio, and both open and closed loop operation.

Figure 5 shows a diagram of the experimental configuration. The general procedure was to change the engine/vehicle parameter, allow the vehicle to stabilize (usually a minute or two), and drive the vehicle from the staging area to pre-conditioning "Point A" and then on to "Start Point B" . This distance was used to stabilize all test conditions (i. e. speed , gear, either steady-state driving or slight acceleration), such that when the vehicle arrived at point "B" the test condition was established. The test condition was maintained constant from point "B", past the remote sensor site on to point "C", where the vehicle was slowed to a stop. It was during this test period (point " B" to point "C") that the data from on-board instrumentation was collected, and the actual "pass point was noted during the data collection. The same conditions were repeated in the opposite direction, reversing the process. The same conditions were repeated a minimum of three times (usually 5 to 10 times).

DYNAMOMETER TESTS

On the last day in Dearborn, the Taurus was tested on a chassis dynamometer where a comparison of the Taurus on-board NO instrument with a conventional chemilumenscence instruments (CLD) was conducted. The vehicle was driven on the dynamometer under conditions which spanned those encountered in the Proving Ground studies.

RESULTS

FACTORS AFFECTING THE NO FEAT SYSTEM

As mentioned above the FEAT system was standardized using a cylinder with known CO, CO_2, propane and NO content in such a manner as to simulate the exhaust of a passing vehicle. This cylinder is the first ever prepared with these gases by Scott

Specialty Gases in Longmont, Colorado. Scott initially reported trouble with stability of the NO content. Inter-calibrations of both detectors with this cylinder and another cylinder (containing CO, CO_2 and propane only) gave results within the expected errors for CO and HC, and within 10% of the laboratory values. The NO calibrations were more difficult to obtain free of noise. More purging of the system was required to obtain good NO calibrations than for CO or HC.

Mechanical vibration causes more noise on the on-road UV NO channel than on the IR channels, thus NO readings are more often rejected than HC or CO unless great care is taken to stabilize the instrument. In El Paso the light source and detector were not always stable. Between the El Paso and Dearborn studies a new (and much more stable) undercarriage was built for the source. In Dearborn, the first day of intercomparison seemed to suffer from instability. The problem was solved by inserting a metal wedge on the last two days between the FEAT detector leg and the metal body.

WATER AND AIR/FUEL CORRECTIONS

In the process of analyzing raw exhaust, the conventional analysis systems remove water from the sample by chilling the exhaust below the dew point. The on-board FTIR instrumentation analyzes a diluted sample which also lowers the dew point without water removal. The Taurus NO analysis is also based on a diluted sample without water removal, however, the Taurus on-board measurements of CO, HC, O_2, and CO_2 is based on a dried sample. The FEAT NO measurements are based on combustion equations relating to "dry exhaust" at stoichiometry (corrections are made for the amount of excess air leaner than stoichiometry). Thus, prior to comparison with the FEAT NO results, one must convert both the OBE and the Taurus NO measurements to "dry exhaust" measurements. The water analysis provided by the on-board FTIR was used to convert the OBE data to "dry exhaust" equivalents. Since the Taurus on-board instrumentation does not include a real-time water analysis, the results were corrected using the amount of water predicted by the combustion equation. This calculation was performed assuming the C/H ratio of fuel to be 1.85, and correcting for additional air-to-fuel ratio effects.

ANALYTICAL PERFORMANCE OF THE ON-BOARD FTIR

During the past year several tests were conducted to evaluate and verify the performance of the Aerostar on-board emissions equipment. These tests include comparison studies with gas standards and correlations with conventional dynamometer instrumentation for both steady-state and modal driving (UDDS). Details and specific results of all tests are given in the CRC VE-11-1 Final Report. The following is a summary of the information contained in that report.

Analyses of gas standards using the on-board FTIR and associated software gave results within 4% of the standard values for NO and CO_2 in all cases. The analyses of the CO standards indicate that the FTIR performs quite well at ~100 ppm range (average error <3%), but the errors in the FTIR analyses increase slightly with increasing CO concentration levels (average error ~6%). While the errors associated with the FTIR analyses of NO standard gases are fairly random, the errors associated with the FTIR analyses for CO and CO_2 are consistently positive, resulting in FTIR analyses which are slightly higher than the label values for the standard gases.

Results of the cruise and modal studies show that for CO_2 the differences between the OBE system and the conventional analyzers is less than 6% in all cases. The error associated with the OBE analyses of CO_2 emissions were fairly random, but on the average the OBE results were 1% lower than the conventional analyzer results. In the case of CO, the agreement between analyzers is better than 6%, and for all cases except one, the OBE results were higher than the conventional analyzer results, averaging 3% higher for the OBE system. Finally, for NO, the agreement between the analyzers is within 13%. The OBE results for NO are, in all cases, consistently lower (an average difference of 10%) than the conventional analyzer results.

As mentioned earlier, prior to the analysis of the raw exhaust samples by the conventional means the samples are chilled and filtered to remove any water and particulate matter in the exhaust. Losses of NO might occur during these processes. Similarly, if the OBE sampling and dilution system were condensing water in any area of the system prior to proper dilution, similar losses might occur. It is important to note that no evidence for condensation of water in the raw exhaust was found in the OBE sampling system. The variable agreement between the conventional analyses and the OBE analyses of NO in vehicle exhaust is currently under further investigation.

TAURUS DYNAMOMETER TESTS

The Taurus was tested on a chassis dynamometer where a comparison of the Taurus on-board NO instrument to a conventional chemilumenscence instruments was conducted. Figure 6 shows the result of the dynamometer intercomparison. The slope of 0.8 arises because on-board measurements are of "wet exhaust" whereas dynamometer measurements are on a dry basis, and the on-board dilution flow, which may be pressure dependent, was calibrated in Denver. The correlation ($R^2 = 0.97$) shows that the on-board system has noise less than $\pm$ 100 ppm (one sigma) at low NO levels (<1000 ppm).

INTERCOMPARISON OF ON-BOARD TAURUS MEASUREMENTS AND NO REMOTE SENSOR

Figure 7 shows NO comparison data (vs. time) from the Taurus drive-bys on Wed. April 22. More than 90% of the vehicle passes resulted in the system reporting valid NO readings. The Taurus RCON/VDAS instrumentation was configured to provide a 10 Hz sample rate on all parameters. Emission data points were averaged over a time corrected three second window that occurred as the vehicle passed the remote sensing beam. Real-time displays of vehicle operating conditions and emissions were available to the driver to provide consistent drive cycles. The Taurus NO emissions were varied by commanding different air-to-fuel ratios through the on-board computer and connecting/disconnecting the EGR vacuum hose. In spite of every effort to maintain a constant driving condition, the exact value of the on-board emissions readings varied with load from less than 1,000 ppm to over 3,000. The Taurus was also tested in closed-loop controlled operation with the EGR connected, where the on-board readings never exceeded 450 ppm. The Taurus had a large range of control over its NO emissions from a low on-board reading of 50 ppm to a high of 5400 ppm.

The upper points and line in Figure 7 are the Taurus data displaced upwards by 3,000 ppm. The emissions were maintained approximately constant for ten runs, then intentionally altered. The jumps can be clearly observed. The lower points and line are the reported remote sensor NO readings. The lines are added to guide the eye and have no scientific meaning. From this graph it is apparent that the remote sensor can distinguish between low and high emitting modes. However, the FEAT NO readings show considerably more scatter than the on-board. The last few points, for instance, show low and consistent on-board readings while the FEAT NO readings vary from 800 to -750 ppm. Despite this variability it is apparent that the FEAT NO detector can distinguish an individual vehicle's high NO (3,000 ppm) passes from low NO passes (<1,000 ppm).

INTERCOMPARISON OF ON-BOARD AEROSTAR MEASUREMENTS AND NO REMOTE SENSOR

As was detailed in the "ON-ROAD TESTS" section above (refer to Figure 5), the test condition was maintained constant from point "B", past the remote sensor site on to point "C", where the vehicle was slowed to a stop. Data from the Aerostar on-board instrumentation was collected while driving from point "B" to point "C", with the OBE FTIR collecting an integrated sample every three seconds, The distances from point "B" to the actual "pass point" and in reverse from point "C" to the actual "pass point were selected to insure sufficient numbers of three second samples to establish a confident data set. Figures 8, 9, and 10 show the individual three second analyses for NO, CO_2, and CO for a typical slight acceleration drive-by. (The steady-state drive-bys are typically more stable.) These figures clearly show stable emissions, ± 100 ppm for

NO and CO and 0.1% for CO_2, during the drive-by.

Since the sampling rate of the remote sensor is high, 100 Hz averaged for 0.5 second, the question arose as to the short term stability of the NO emissions from the Aerostar. To address this issue, dynamometer tests were conducted where the second-by-second NO emissions were measured using the dynamometer cell chemilumenscence analyzer (CLD). These measurements were made while the vehicle was operated at a steady-state condition for approximately 100 seconds, then accelerated to a new steady-state speed 5 mph greater. The range of vehicle speeds were from 25 mph to 40 mph. The results are shown in Figure 11. Again the variability in NO emissions during the steady state modes is about 200 ppm confirming that the variability in the FTIR three second integrated measurements shown in Figure 8 is probability representative of the vehicle NO emissions.

The FEAT NO sensor measures the ratio NO/CO_2 in the exhaust plume and the concentration of NO in the exhaust is calculated from the "dry" combustion equation as discussed in the section above (Water and Air /Fuel Corrections). The most direct and accurate comparison of results from the Aerostar on-board measurements to the FEAT NO sensor is accomplished by comparing the NO/CO_2 ratio from the FTIR analysis of the vehicle exhaust to the FEAT measured NO/CO_2 ratio. This not only avoids corrections for air dilution and exhaust water concentrations but eliminates assumptions for engine/vehicle operating parameters. The results comparing these ratios is shown in Table 3. This table gives the vehicle drive-by conditions, the on-board NO and CO_2 measurements, the corresponding remote sensing data, and a comparison of the ratios measured by the two techniques. Under the heading "Vehicle Conditions" is given the vehicle velocity at the "pass point", the pre-set air/fuel ratio as lambda, and the test conditions: steady-state or slight acceleration (ss or sa), the transmission gear (2nd or 3rd), the engine control condition [open loop (o) or closed loop (c)], and the number of drive-by tests averaged for each condition. The data given for the last two conditions in Table 3 [20 mph, $\lambda = 1.1$, slight acceleration, 2nd gear] was directionally dependent and was treated as separate points northbound (n) and southbound (s) (discussed later). Also shown in Table 3 are the individual averaged on-board emissions measurements for both NO and CO_2 and percent standard deviations in those measurements based on the number of drive-by tests shown in the column labeled condition. From these emissions data are calculated the NO/CO_2 ratios and the percent standard deviation for the ratios (This value is based on the standard deviation of the individual ratio of NO/CO_2 for each drive-by test point). The column labeled RS Data gives the average NO/CO_2 ratio measured by the FEAT NO sensor for each condition and the corresponding percent standard deviation. The last column ratios the measured OBE NO/CO_2 to the Remote sensor measured NO/CO_2 ratio. Finally the average of the ratios of the two techniques along with the standard deviation and percent standard deviation is given. The average shows that the two techniques agree to within 10% for all conditions tested but the standard deviation is large (39%). The major contributor to the large standard deviation is the remote sensor measurements, where the percent standard deviation averages 23%. The complete test data for the Aerostar Proving Ground study is given in Appendix 1.

Figure 12 shows the agreement of the two techniques as a function of the Aerostar NO emissions. The remote sensing technique overestimates the NO emissions at the lowest Aerostar emissions levels (754-1134 ppm, i. e. 20 mph, λ = 1.1, slight acceleration test condition), but underestimates the NO emissions at the highest emissions rate (1941 ppm, i. e. 35 mph, λ = 1.1, slight acceleration). Examining the agreement with respect to vehicle speed (Figure 13) shows the remote sensor measurement of NOx from the Aerostar appears to be vehicle speed dependent.

CORRELATION FROM ALL VEHICLE TESTS

The data from both the Taurus and Aerostar are combined in Figure 14. The Aerostar had a smaller range of emissions available, from a low of 750 to a high of 2660. The Taurus NO emissions ranged from ~50 ppm to as high as 5500 ppm. The slope of the regression analysis of the data is 0.757. The departure from unity is likely due to differences in the calibrations. The stated uncertainty from the regression is R^2 = 0.54 (uncertainty is ± 860 ppm) which we believe is mainly attributable to uncertainty in the remote sensing readings.

NO EMISSION VARIABILITY

The concentration of NO in the raw exhaust of the uncatalyzed vehicle is far more variable with cruise speed than are the concentration levels of CO or CO_2. The NO levels in the raw exhaust samples ranged from ~850 to 2850 ppm. Similarly, the uncertainty associated with the OBE analyses of NO in the dilute exhaust samples (ranging from ~85 to 285 ppm NO) were quite variable, ranging from 1 to 13%. This was not the case for the OBE analyses of the gas standard containing NO, where the uncertainty associated with the NO analyses were no greater than 4%, and varied little at any given concentration level (< 1% rsd). Several factors might contribute to the variable uncertainty of the OBE or the dynamometer cell analyses of NO in vehicle exhaust samples. One factor is water condensation effects. NO is more reactive than CO or CO_2, and in the presence of high concentrations of water or other reactive compounds, such as those typically found in vehicle exhaust, chemical and/or physical losses of NO might be possible. A second effect may be variable emission rates due to fluctuating catalyst/engine temperature.

THE EFFECT OF CATALYST/ENGINE TEMPERATURE ON NOx EMISSIONS

The NOx emissions observed with the Aerostar during the on-road tests were less reproducible than expected based on dynamometer calibration studies. Additional

Aerostar dynamometer tests were conducted with the RCON/VDAS system to investigate the relationship between exhaust gas temperature and NOx emissions. As expected higher NOx emissions were produced at higher exhaust gas temperatures. These higher NOx emissions occurred under conditions similar to the test track studies, namely at constant air/fuel, speed, and load conditions. Figure 15 shows the NOx emissions measured by the Aerostar on-board FTIR as a function of engine exhaust temperature. A blank catalyst was also used in these studies and, therefore, the temperature shown as pre-catalyst is the actual exhaust gas temperature. Figure 16 shows the vehicle speed and measured exhaust gas temperature as well as the on-board measured NO emissions and CO emissions. The NO emissions are highly sensitive to exhaust gas temperature, more than CO emissions, suggesting that driver variability (stability) could greatly affect the consistency of NO emissions even under steady-state conditions. This is not true for the observed CO emissions under the same conditions, and therefore CO would not be a good indicator of low or constant NO emissions.

Similar information was available from the Taurus (Figure 17). The Taurus was equipped with a production catalyst and the changing emissions effects are different the the Aerostar with a blank catalyst. The more slowly changing thermal inertia followed by a rapid increase when the catalyst is over burdened further confuses the effect.

CONCLUSIONS

The Intercomparison study performed at the Dearborn Proving Ground leads to several conclusions. The first is that the FEAT system measures vehicle NO emissions with an error of about 860 ppm. Since the reported error bars during calibration are less than 50 ppm and instrument vibration is not a problem during calibration, it may be that further attention to eliminating vibration will lower the on-road measurement uncertainties. The second is that 860 ppm noise on an individual reading is small enough that high emitting vehicles (>3,000 ppm) can be distinguished from low emitting vehicles (<1,000 ppm).

Based upon the remote sensing data, it was not possible to drive the Taurus in a closed-loop mode which measured NO greater than 1,000 ppm. When the Taurus was intentionally malfunctioning (EGR disconnected), NO measured above 3,000 ppm in some driving modes and less than 1,000 in others. This suggests that the remote sensor would predict that malfunctioning vehicles could be measured either as high or low emitters (i. e. , they would be "flippers"), whereas a properly controlled vehicle would never be identified as malfunctioning.

The third conclusion is that discrepancies between the on-board and remote sensing techniques may be the result of vehicle speed and vehicle aerodynamics (exhaust plume dispersion). Descrepancies were more pronounced with the Aerostar where a correlation between remote sensor estimation of NO emissions and the on-board instrumentation shows a speed dependency.

Finally it can be concluded that NO emissions from a well tuned vehicle are sensitive to minor perturbations in driving patterns and engine/catalyst conditions. Slight changes in acceleration (i.e., engine speed, throttle position, and load) have significant effects on the NO emissions. A clear example of this was the directional dependence of the 20 mph tests conducted with the Aerostar, where a brisk wind from the north changed the NO emissions from 1148± 23 ppm (headwind direction) to 748± 49 ppm (tail wind direction). This behavior, in combination with the effect of engine/catalyst temperature, suggests that the location of the NO remote sensing site, which impacts test vehicle driving condition and history, may be a more important consideration than it is for CO and hydrocarbon remote sensors.

The study also suggests there is a consistent discrepancy between the on-board NOx instrumentation, whether it be UV (Taurus) or FTIR (Aerostar) , and the conventional dynamometer chemiluminescence analysis, even after "wet" exhaust corrections. The source(s) of these differences should be investigated further especially if dynamometer chemilumenscence data is to be used in real-world models.

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Table 1: List of Components and Detection Limits as Measured by FTIR.

Component	Detection Limit Gas Phase (ppm)	Detection Limit FTP (mg/mi)
Formaldehyde (CH_2O)	0.54	2.3
Methanol (CH_3OH)	1.8	8.0
Carbon Monoxide (CO)	8.9	34
Carbon Dioxide (CO_2)	470	2900
Nitric Oxide (NO)	0.39	1.4
Nitrogen Dioxide (NO_2)	2.8	15
Nitrous Oxide (N_2O)	0.10	0.6
Nitrous Acid (HONO)	2.4	14
Methane (CH_4)	1.7	3.7
Acetylene (C_2H_2)	0.62	2.2
Ethylene (C_2H_4)	1.3	4.9
Ethane (C_2H_6)	0.54	2.3
Propylene (C_3H_6)	4.2	24
Isobutylene ($i\text{-}C_4H_8$)	1.3	10
1,3-Butadiene	1.8	14
Acetaldehyde (CH_3CHO)	3.6	22
Ethanol (C_2H_6O)	0.62	3.9
Formic Acid (HCOOH)	0.39	2.5
Sulfur Dioxide (SO_2)	0.73	6.5
Water (H_2O)	3200	7900
Hydrogen Cyanide (HCN)	0.44	1.6
Ammonia (NH_3)	0.85	2.0
Non speciated HC	5.7	11
SUM Hydrocarbon	19	37
SUM NO_x	3.6	20

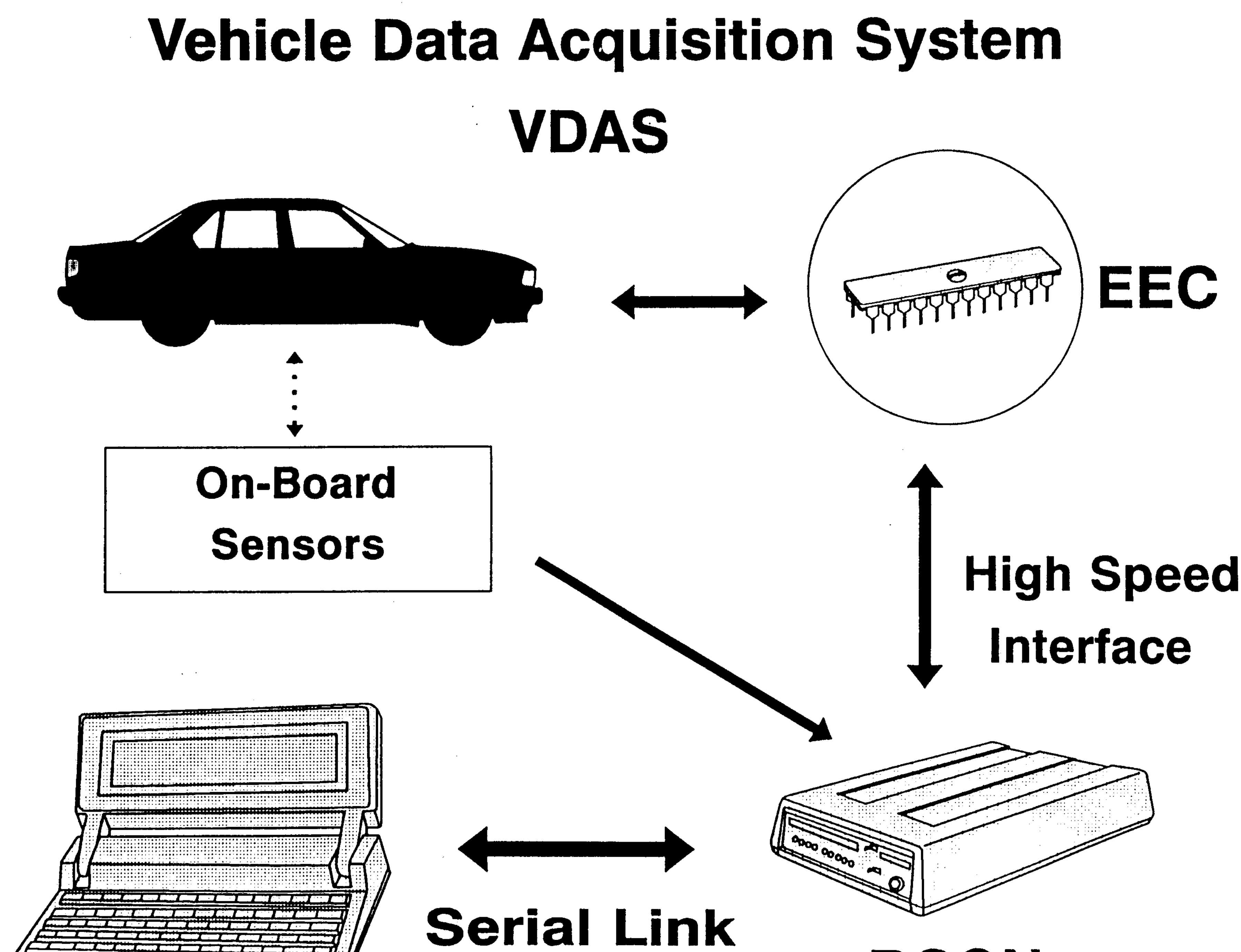
Table 2: Vehicle and Engine Operating Parameters Monitored by VDAS/RCON .

Parameter Name	Significance of Parameter
time	Time in seconds since start of data set
vs	Vehicle Speed (MPH)
n	Engine RPM
apt	Throttle mode flag
load	Air charge per cylinder/standard air charge
lambse1	Calculated air/fuel equivalence ratio
am	Air Mass
tp_rel	Throttle position
ect	Engine Coolant temperature (°F)
act	Air charge temperature (°F)
fuelpw1	Fuel pulse width
accflg	Air conditioner clutch flag
precat	Exhaust gas temperature (°F)
midbed	Catalyst temperature (°F)
lambda	Measured air/fuel equivalence ratio
flow_in	N_2 diluent flow (LPM)
olflg	Open loop flag

Table 3. Intercomparison of On-Board Aerostar Measurements and NO Remote Sensor

Vehicle Conditions			On Board Emissions Data						RS Data		OBE/RS
Velocity	Lambda	Conditions	NO(avg)	%s.d.	CO_2(avg)	%s.d.	NO/CO_2	%s.d.	NO/CO_2	%s.d.	NO/CO_2
30	1.1	ss,2,o,4	1779	4.4	121900	1.0	0.0146	4.3	0.0128	18.4	1.140
35	1.1	ss,2,o,4	1941	8.1	121600	0.6	0.0160	8.6	0.0080	39.4	1.995
35	1.1	ss,2,c,5	1850	7.1	127900	0.2	0.0145	7.0	0.0114	38.3	1.267
35	1.0	ss,3,c,5	1805	18.4	127500	0.8	0.0142	18.0	0.0127	23.1	1.112
30	0.95	ss,3,o,3	1420	6.0	121300	0.5	0.0117	6.3	0.0080	12.1	1.465
30	1.1	sa,2,o,10	1799	7.1	122500	0.8	0.0147	7.5	0.0171	18.1	0.861
30	1.0	sa,2,o,10	1736	13.3	127600	0.6	0.0136	13.3	0.0149	14.9	0.913
20	1.1	sa,2,o,3n	1134	2.0	116300	4.1	0.0098	5.0	0.0165	18.0	0.591
20	1.1	sa,2,o,3s	748	6.0	122000	1.6	0.0061	7.5	0.0119	22.1	0.515

AVG	1.096
S.D.	0.426
%S.D.	39.2



Vehicle Data Acquisition System
VDAS
EEC
On-Board
Sensors
High Speed
Interface
Serial Link
RCON

Figure 1

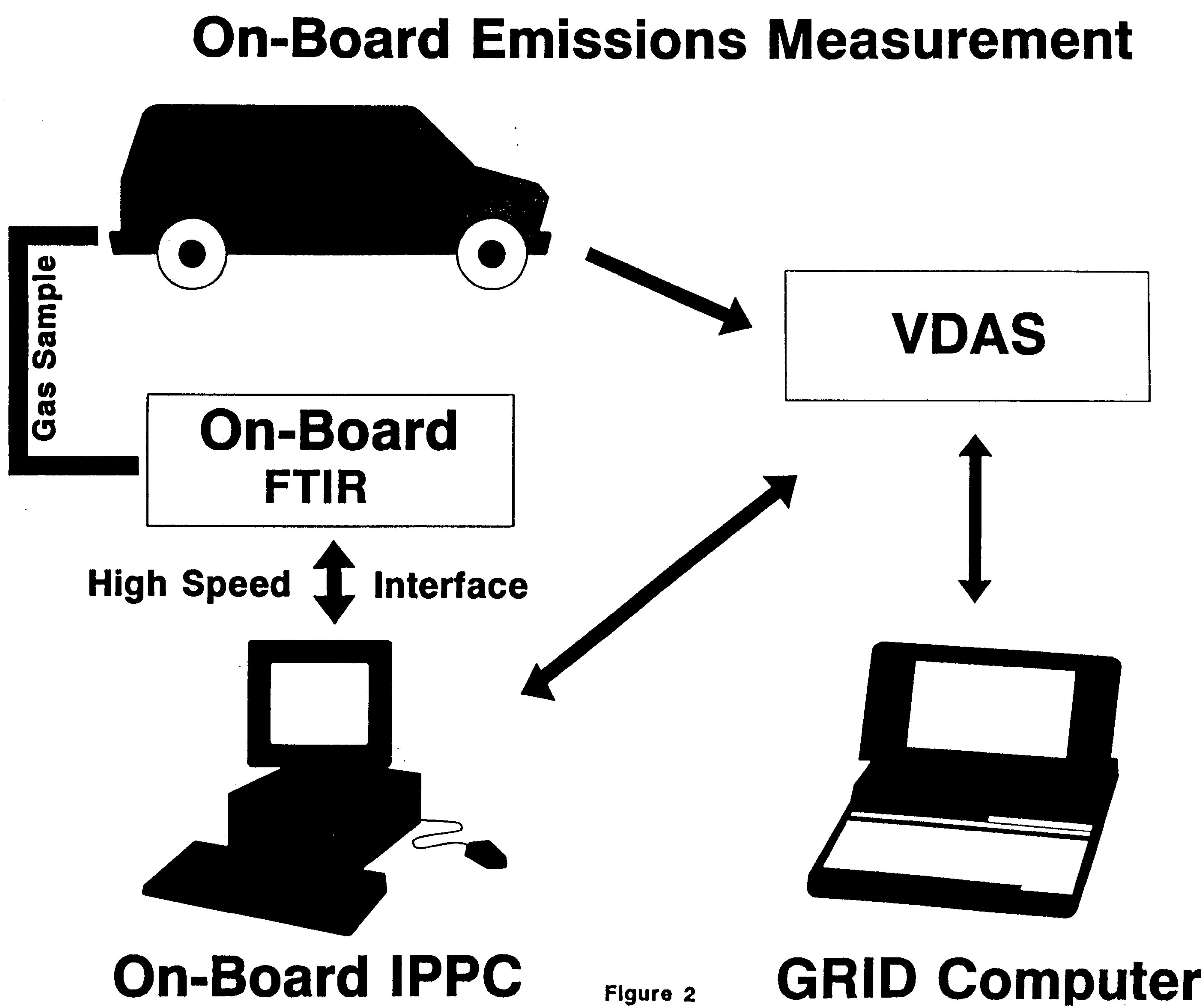
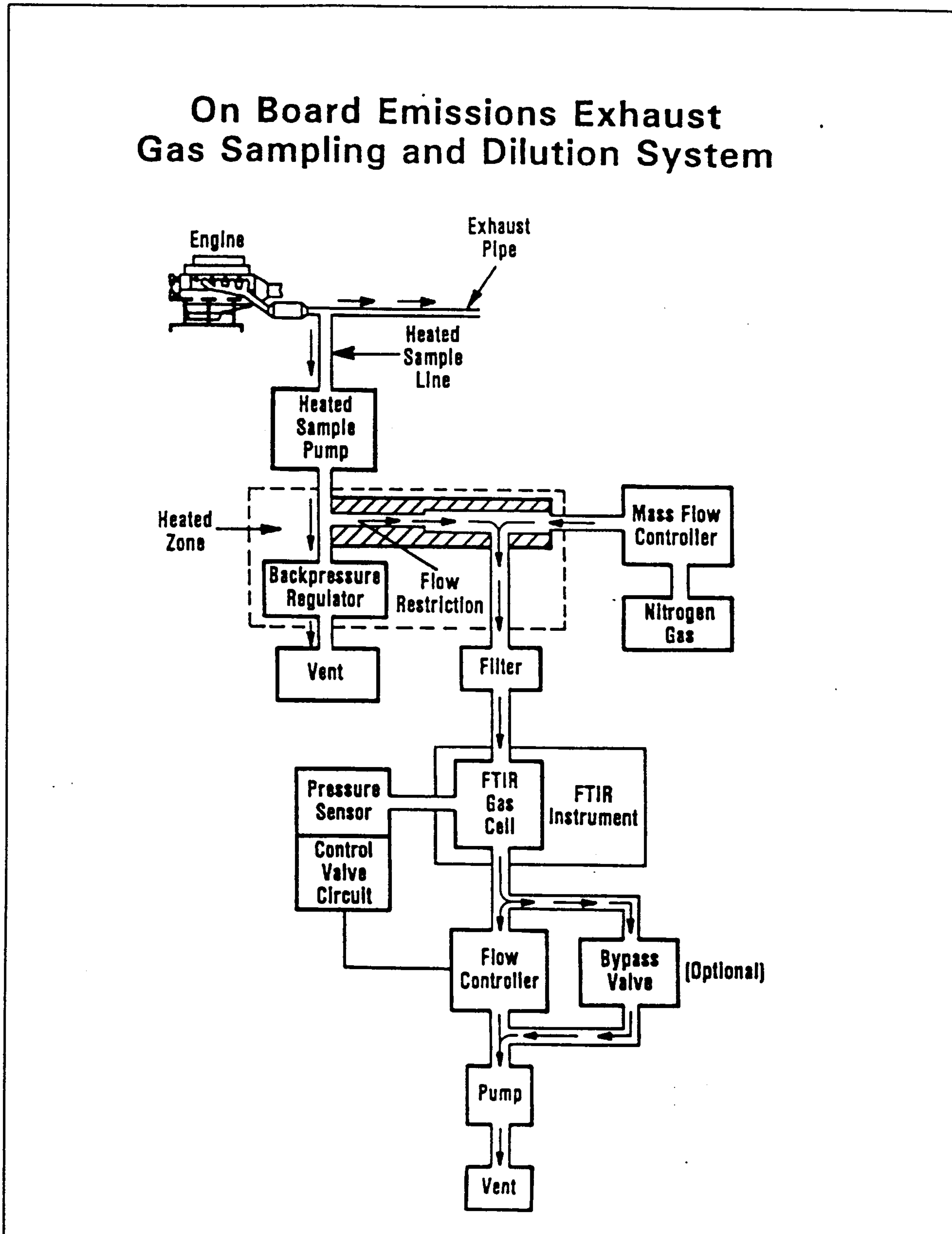

On-Board Emissions Measurement
Gas Sample
On-Board
FTIR
High Speed
Interface
VDAS
On-Board IPPC
GRID Computer

Figure 2

Figure 3


On Board Emissions Exhaust Gas Sampling and Dilution System
Engine
Exhaust Pipe
Heated Sample Line
Heated Sample Pump
Heated Zone
Backpressure Regulator
Flow Restriction
Mass Flow Controller
Nitrogen Gas
Vent
Filter
Pressure Sensor
Control Valve Circuit
FTIR Gas Cell
FTIR Instrument
Flow Controller
Bypass Valve
(Optional)
Pump
Vent

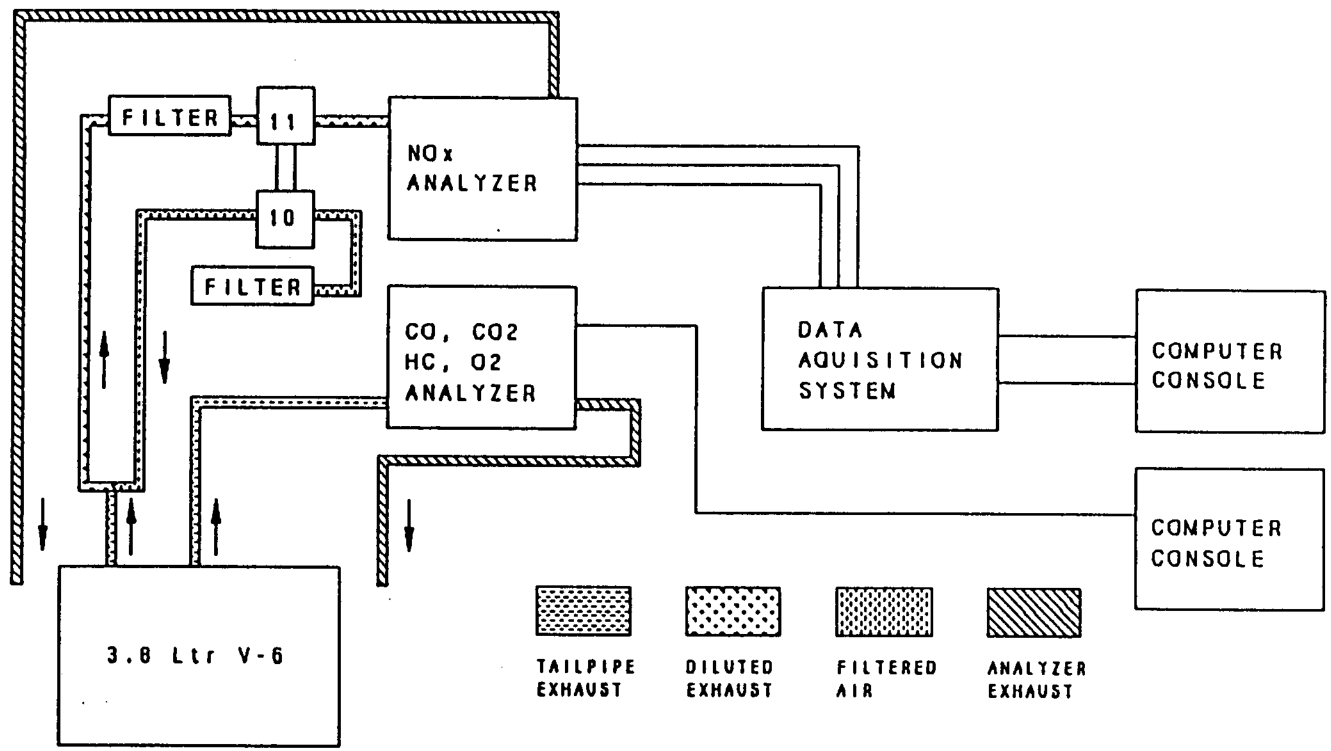


DIAGRAM OF ON BOARD EMISSIONS MEASUREMENT SYSTEM

Figure 4

On-Road Vehicle Tests
Site Diagram

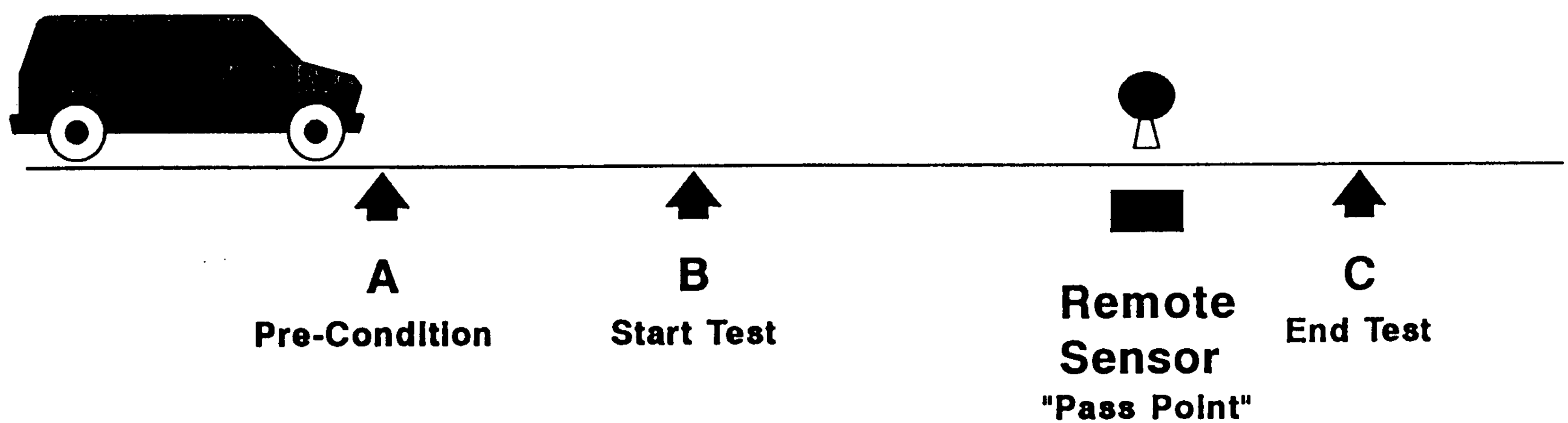


Figure 5

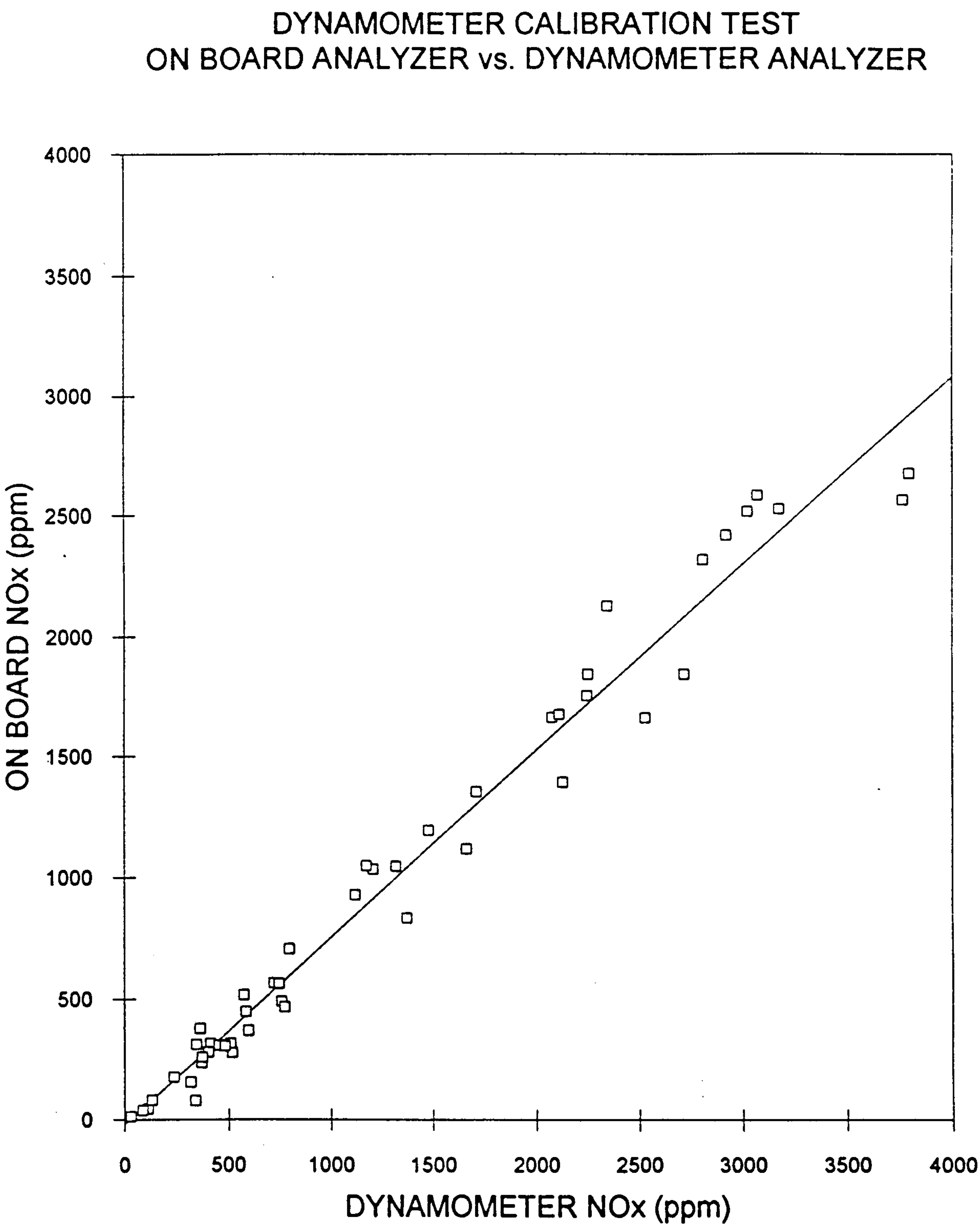

DYNAMOMETER CALIBRATION TEST
ON BOARD ANALYZER vs. DYNAMOMETER ANALYZER
ON BOARD NOx (ppm)
DYNAMOMETER NOx (ppm)
0
500
1000
1500
2000
2500
3000
3500
4000

FIGURE 6

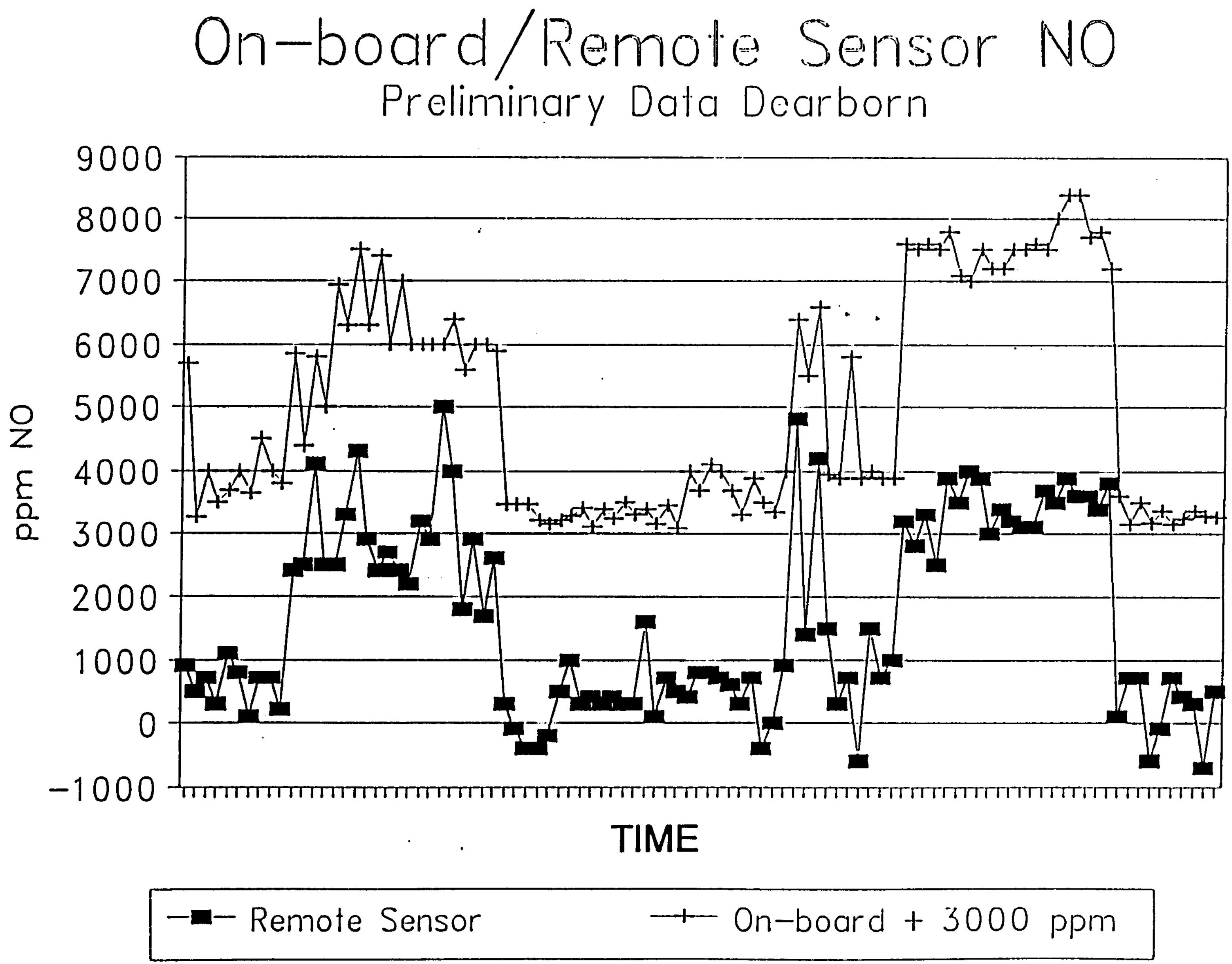

On-board/Remote Sensor NO
Preliminary Data Dearborn
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
ppm NO
TIME
Remote Sensor
On-board + 3000 ppm

Figure 7

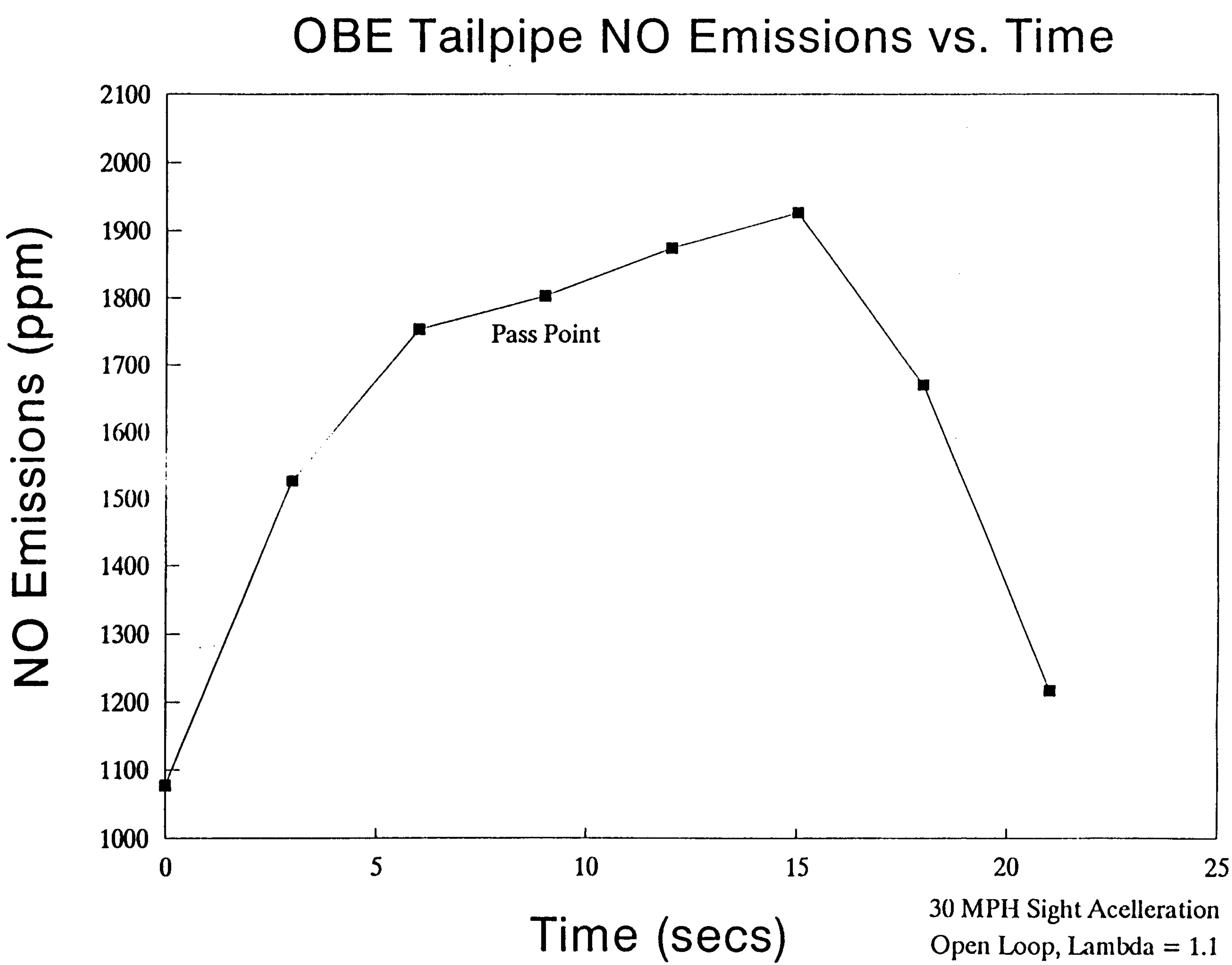

OBE Tailpipe NO Emissions vs. Time
NO Emissions (ppm)
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Pass Point
0
5
10
15
20
25
Time (secs)
30 MPH Sight Acelleration
Open Loop, Lambda = 1.1

Figure 8

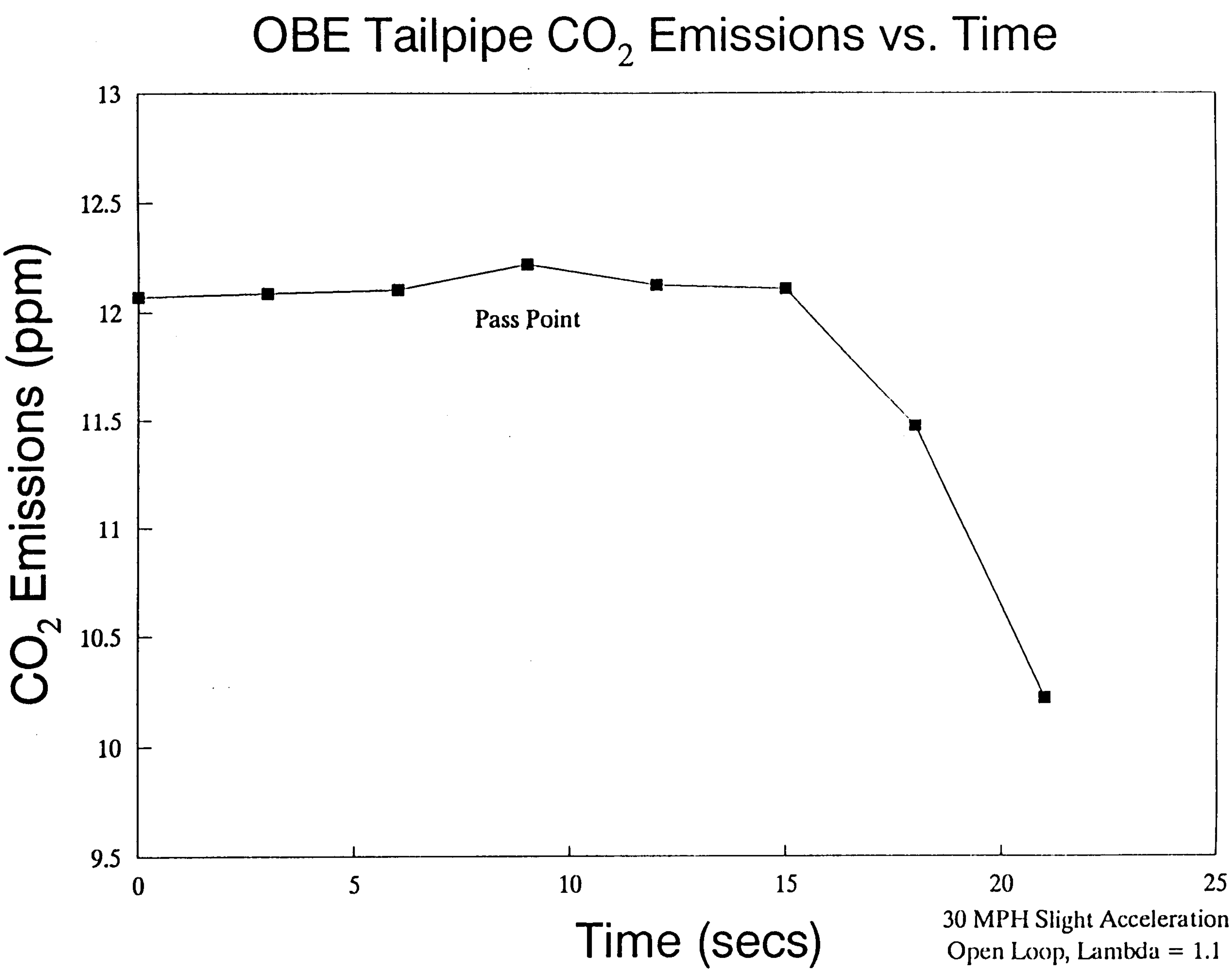

OBE Tailpipe CO_2 Emissions vs. Time
CO_2 Emissions (ppm)
13
12.5
12
11.5
11
10.5
10
9.5
0
5
10
15
20
25
Pass Point
Time (secs)
30 MPH Slight Acceleration
Open Loop, Lambda = 1.1

Figure 9

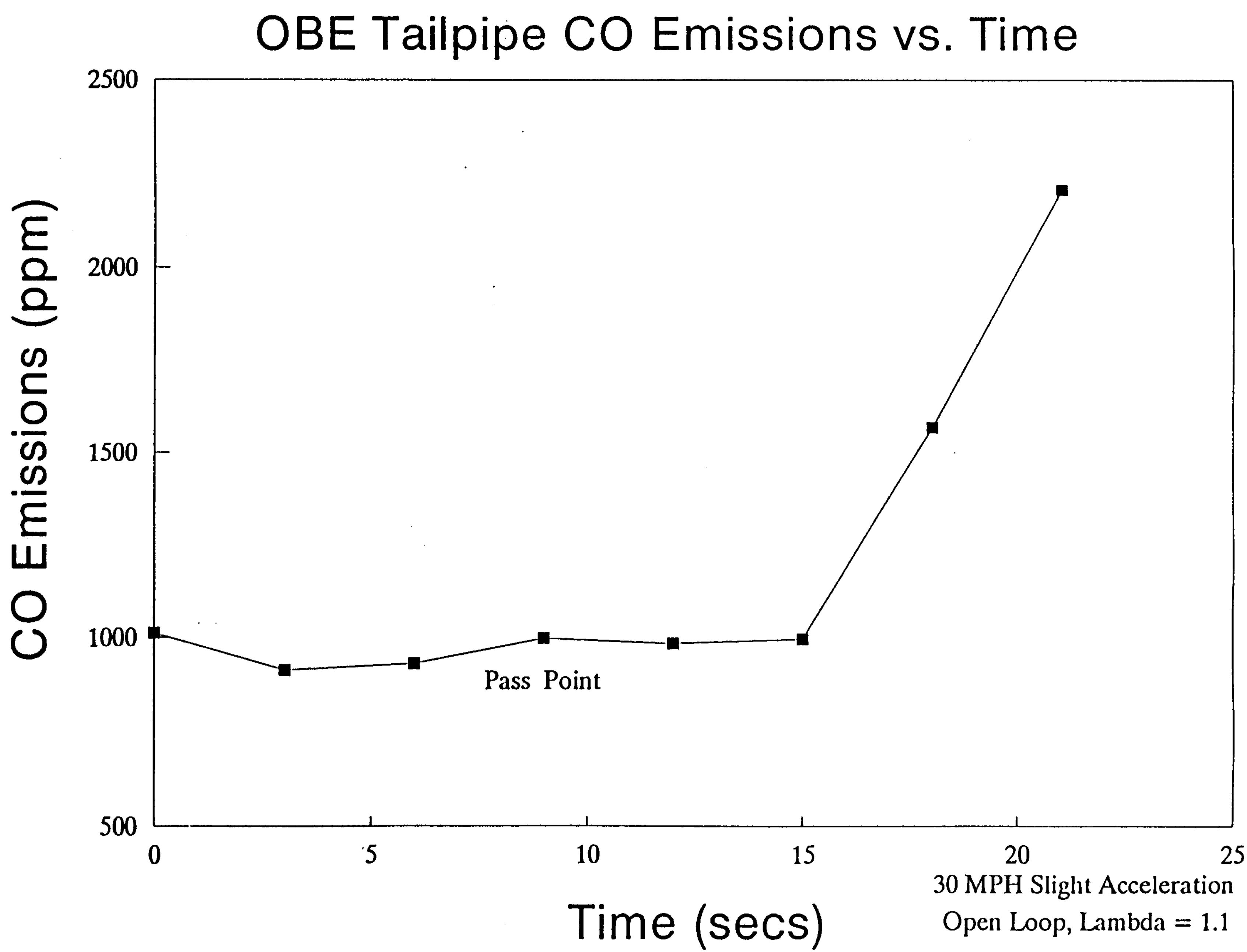

OBE Tailpipe CO Emissions vs. Time
CO Emissions (ppm)
2500
2000
1500
1000
500
0
5
10
15
20
25
Pass Point
30 MPH Slight Acceleration
Open Loop, Lambda = 1.1
Time (secs)

Figure 10

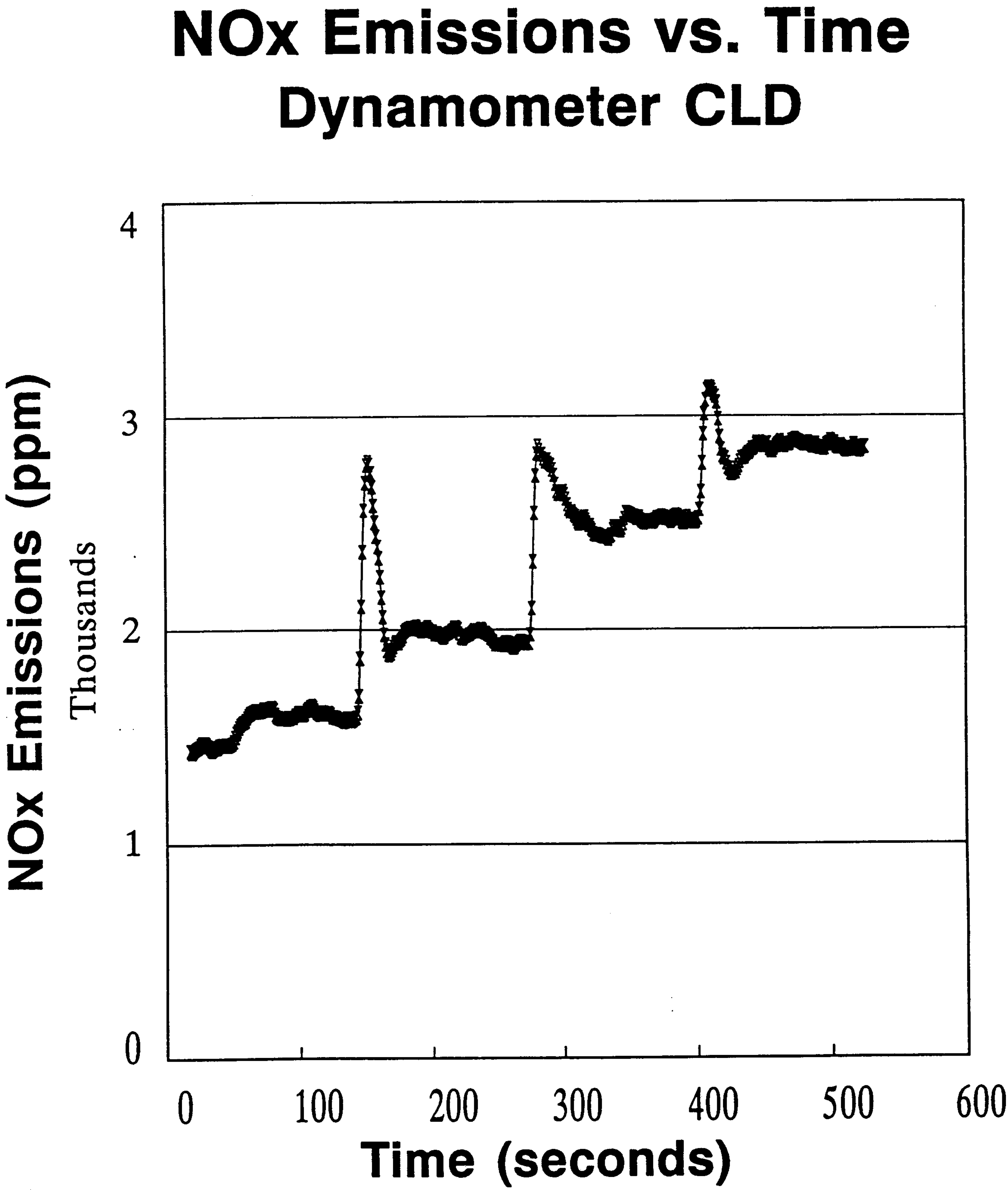

NOx Emissions vs. Time
Dynamometer CLD
NOx Emissions (ppm)
Thousands
0
1
2
3
4
0
100
200
300
400
500
600
Time (seconds)

Figure 11

On-Board Emissions vs. Remote Sensor

OBE/RS [NOx/CO2] vs. OBE NOx Concentration

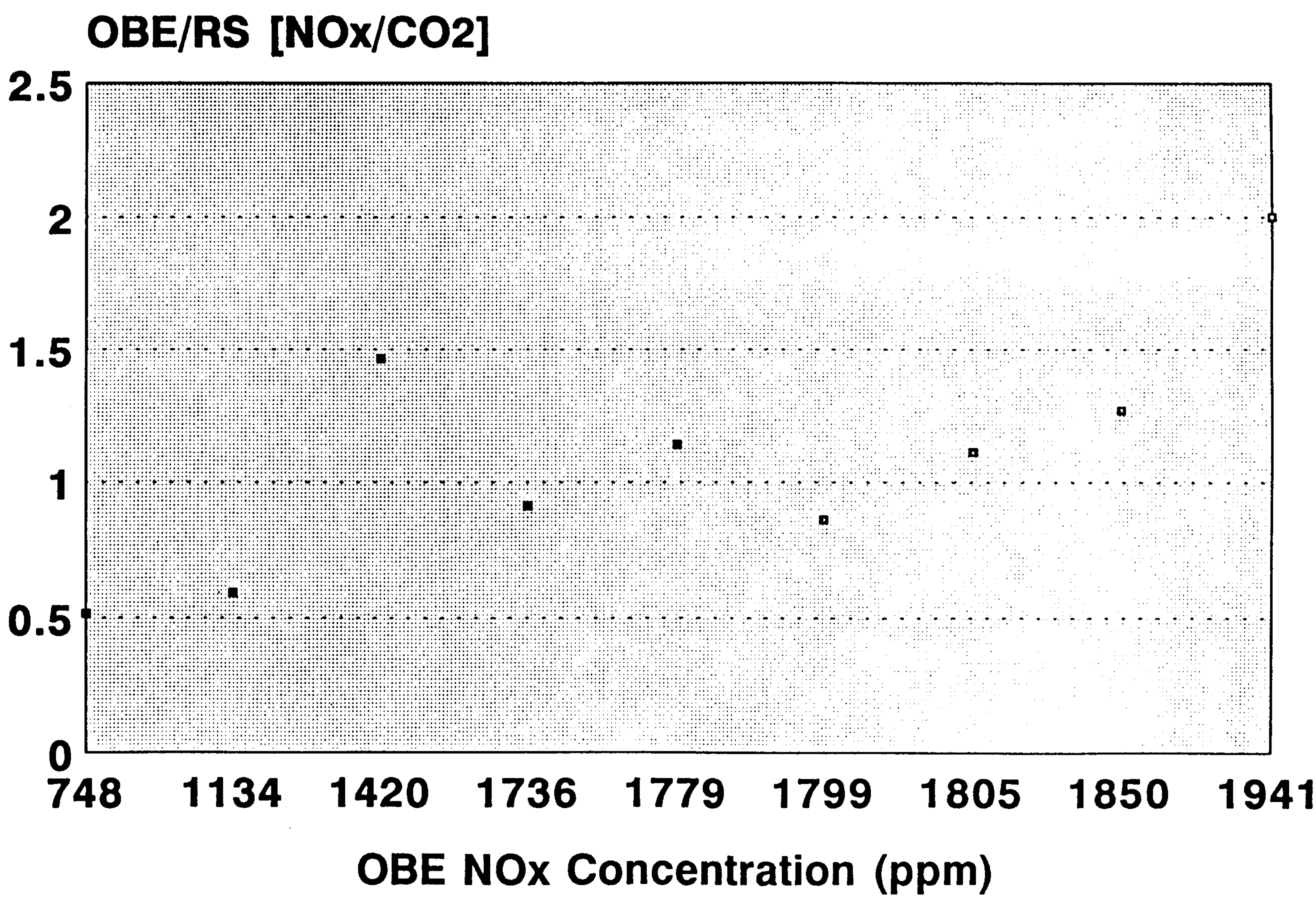


Figure 12

On-Board Emissions vs. Remote Sensor

OBE/RS [NOx/CO2] vs. Vehicle Speed

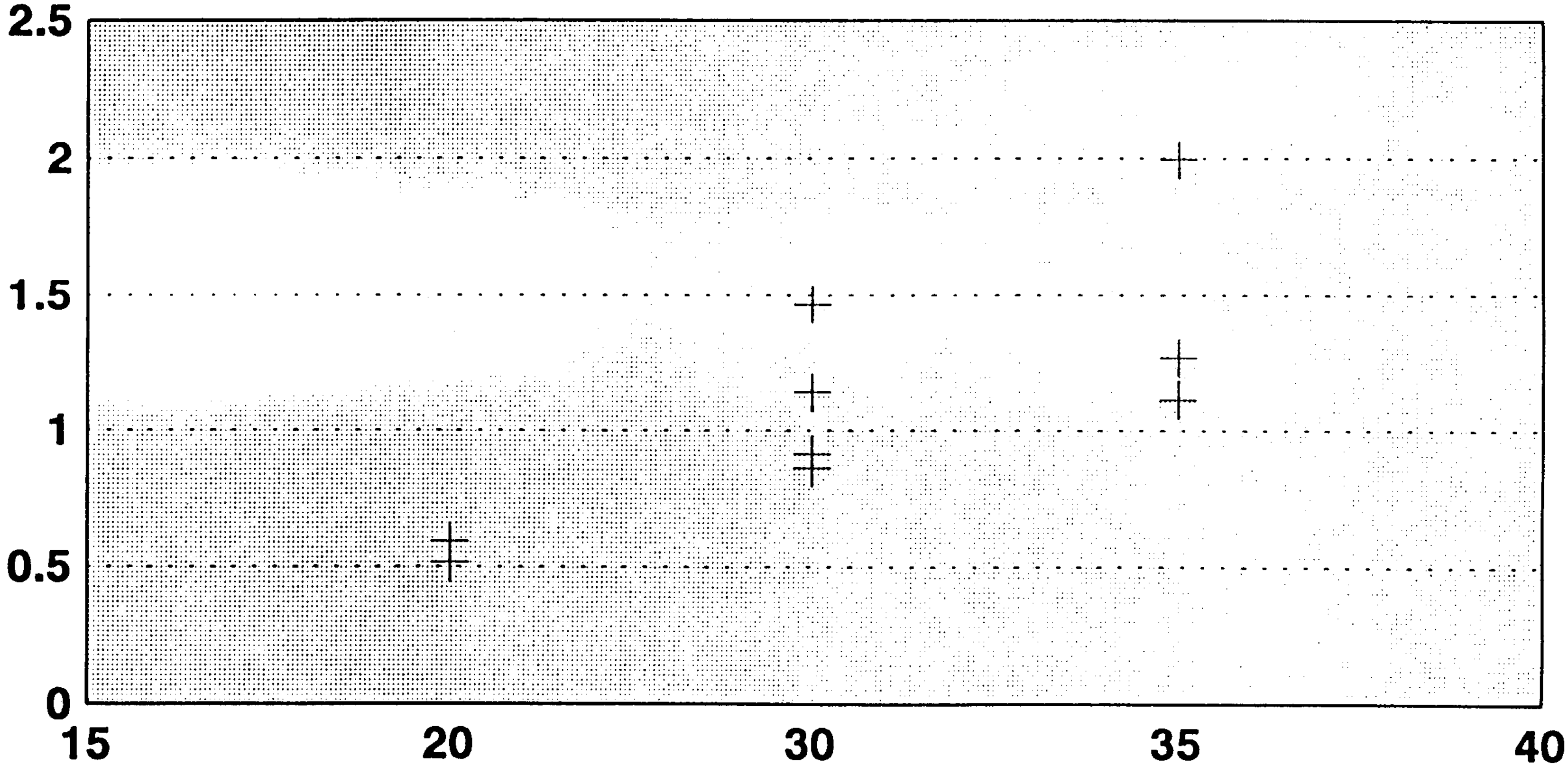


Figure 13

Comparison of Remote Sensor and On-Board Measurements

Dearborn Test Data

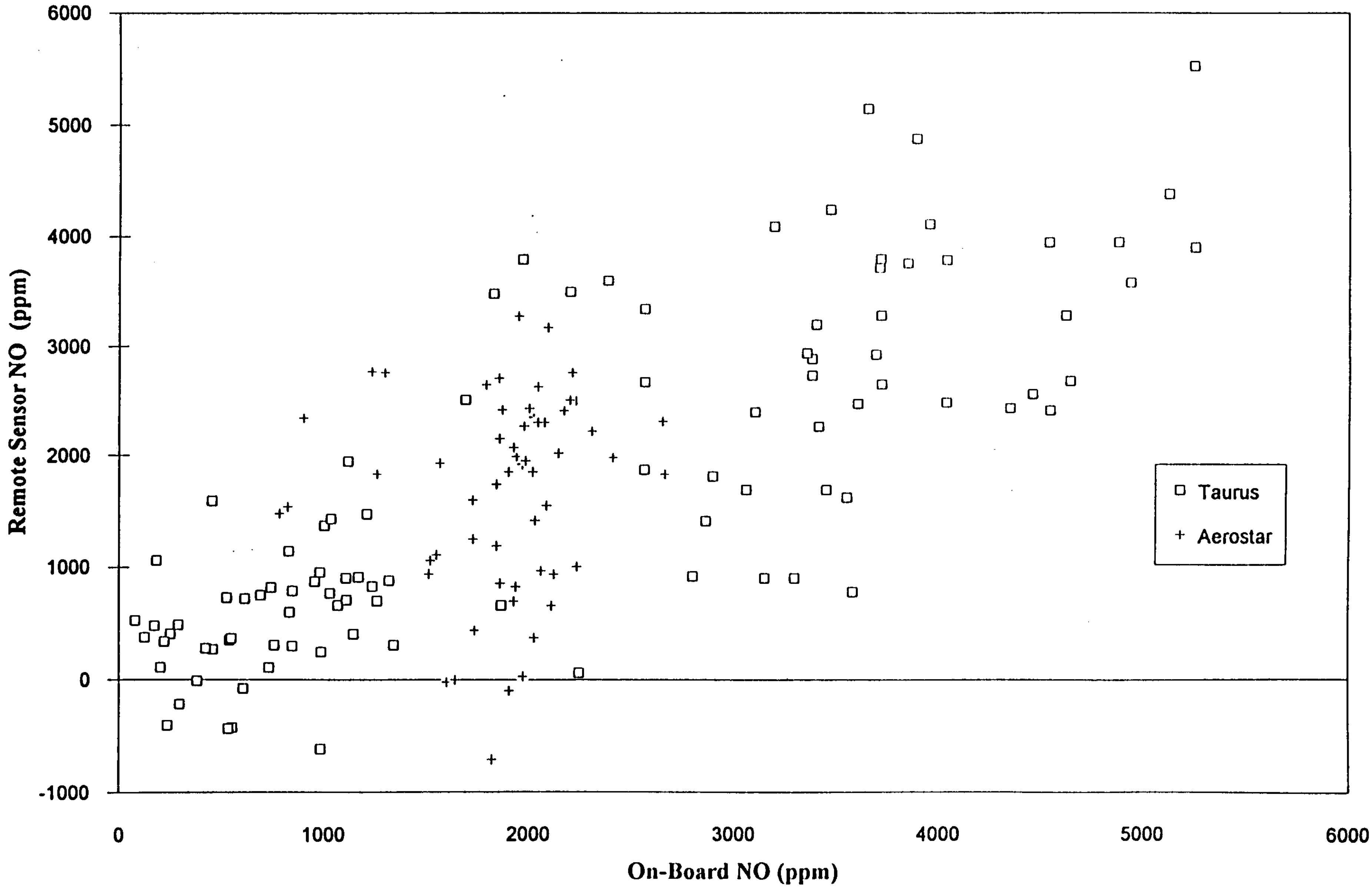


Figure 14

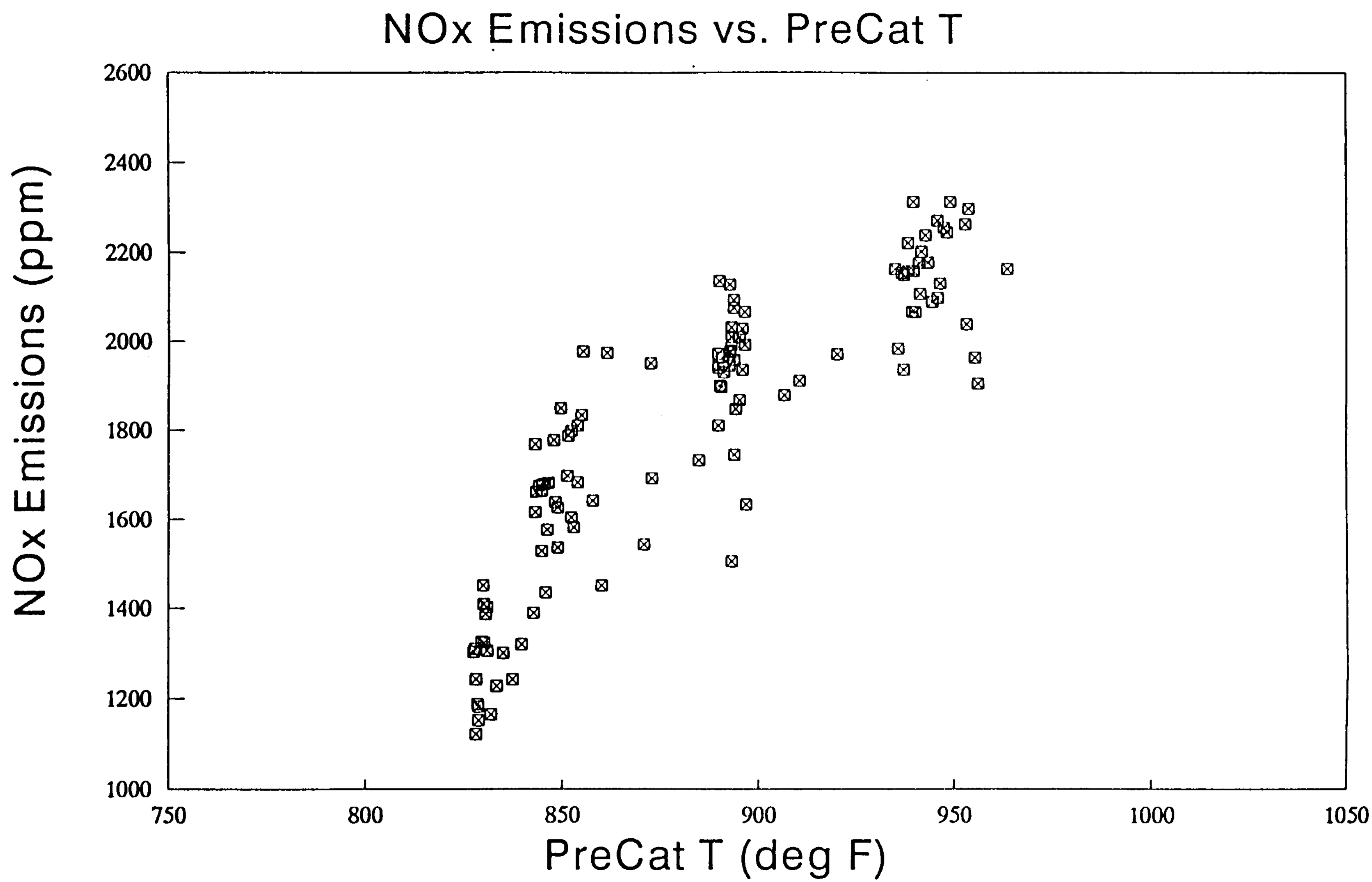

NOx Emissions vs. PreCat T
2600
2400
2200
2000
1800
1600
1400
1200
1000
NOx Emissions (ppm)
750
800
850
900
950
1000
1050
PreCat T (deg F)

Figure 15

Effect of Speed and Pre-Catalyst Temperature
Aerostar Test Vehicle

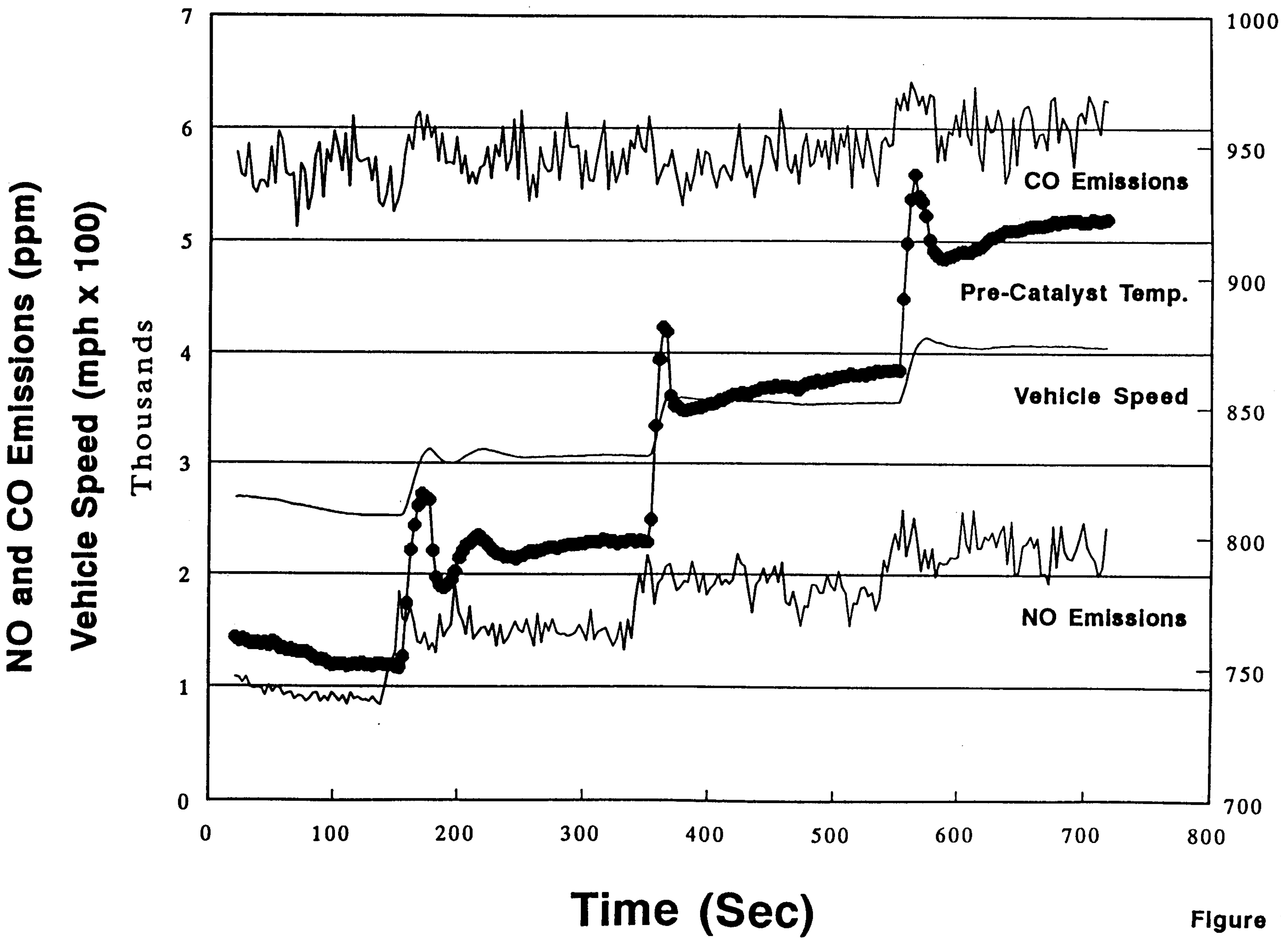


Figure 16

Effect of Speed and Pre-Catalyst Temperature

Taurus Test Vehicle

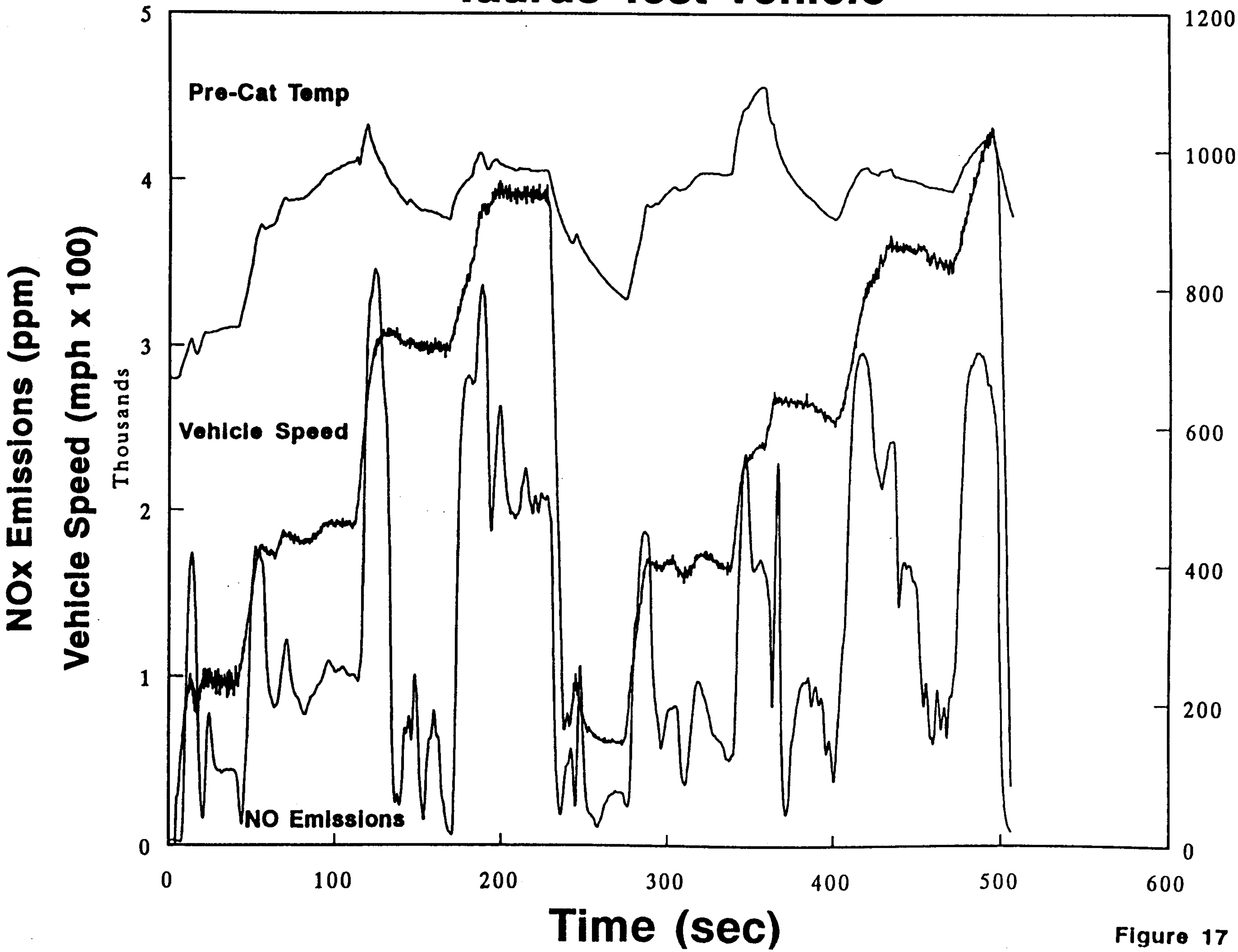


Figure 17

APPENDIX 1: AEROSTAR AND REMOTE SENSOR DATA ACQUIRED AT THE DEARBORN PROVING GROUNDS

Trial	Lambda		Dilution Factor		Speed (mph)	
No.	AVG	STD	AVG	STD	AVG	STD
1	1.09	0.01	10.92	0.22	27.13	0.73
2	1.11	0.02	11.09	0.16	31.30	0.93
3	1.07	0.00	10.82	0.43	29.04	0.73
4	1.10	0.01	10.56	0.18	30.95	1.19
5	1.07	0.01	11.34	0.35	27.79	0.91
6	1.11	0.02	11.04	0.11	30.98	1.04
7	1.08	0.01	11.22	0.55	29.27	1.01
8	1.08	0.01	11.68	0.42	29.62	1.64
9	1.10	0.02	10.65	0.14	27.64	1.01
10	1.10	0.03	11.32	0.47	29.80	1.25
AVG	1.09		11.06		29.35	
%RSD	1.33		2.93		4.78	
11	0.97	0.00	11.52	0.08	29.35	1.18
12	0.97	0.01	11.09	0.08	29.00	0.99
13	0.96	0.01	11.22	0.78	31.09	1.22
14	0.97	0.01	10.85	0.43	29.12	1.43
15	0.99	0.01	10.64	0.33	31.58	1.30
16	0.99	0.01	11.40	0.02	28.31	0.93
17	0.97	0.01	10.80	0.27	28.07	1.33
18	0.99	0.01	11.40	0.41	30.44	1.19
19	0.98	0.00	11.68	0.43	29.75	1.14
20	0.97	0.03	10.45	0.23	31.25	1.19
AVG	0.98		11.11		29.80	
%RSD	1.04		3.48		3.95	
21	1.08	0.01	10.26	0.91	21.57	1.32
22	1.10	0.02	10.84	0.21	20.69	1.16
23	1.09	0.01	10.65	0.18	22.81	2.17
24	1.08	0.01	11.14	0.37	21.02	1.43
25	1.10	0.02	10.94	0.56	21.95	1.81
26	1.09	0.01	10.89	0.70	20.83	1.84
AVG	1.09		10.79		21.48	
%RSD	0.75		2.56		3.43	
27	1.07	0.02	10.97	0.42	27.88	0.77
28	1.16	0.06	10.72	0.14	29.79	1.59
29	1.12	0.05	10.95	0.10	30.39	0.53
30	1.07	0.00	10.66	0.17	30.95	0.14
31	1.08	0.01	11.31	0.31	30.83	0.14
32	1.10	0.03	10.73	0.80	29.79	1.03
33	1.08	0.00	11.37	0.23	30.61	0.09
34	1.08	0.00	10.55	0.32	30.66	0.14
35	1.10	0.02	10.92	0.10	30.41	0.12
36	1.10	0.02	11.24	0.57	30.32	0.19
AVG	1.10		10.94		30.18	
%RSD	2.39		2.48		2.80	
37	1.14	0.05	10.95	0.27	34.80	1.48
38	1.15	0.07	11.21	0.25	34.80	1.48
39	1.11	0.03	10.90	0.14	33.64	1.40
40	1.12	0.03	11.01	0.34	35.11	0.21
AVG	1.13		11.02		34.59	
%RSD	1.40		1.07		1.62	
41	1.01	0.02	10.98	0.08	32.68	1.42
42	0.99	0.01	11.70	0.24	34.92	1.28
43	0.99	0.01	10.66	0.34	32.94	1.30
44	0.99	0.01	11.06	0.35	32.94	1.30
45	1.02	0.02	11.11	0.45	32.94	2.38
AVG	1.00		11.10		33.28	
%RSD	1.26		3.04		2.48	
46	0.99	0.00	10.86	0.50	35.15	0.47
47	1.02	0.03	10.98	0.04	34.99	0.58
48	1.01	0.02	11.40	0.45	35.58	0.69
49	1.00	0.01	11.49	0.49	33.96	1.03
50	0.99	0.01	11.23	0.15	35.26	0.10
AVG	1.00		11.19		34.99	
%RSD	1.18		2.15		1.57	
51	0.93	0.00	10.78	0.26	29.57	0.53
52	0.94	0.00	11.27	0.18	30.26	0.80
53	0.93	0.01	10.97	0.36	29.92	0.42
54	0.93	0.01	11.00	0.34	30.74	0.40
AVG	0.93		11.01		30.12	
%RSD	0.48		1.59		1.43	

APPENDIX 1: AEROSTAR AND REMOTE SENSOR DATA ACQUIRED AT THE DEARBORN PROVING GROUNDS

Trial No.	Aerostar OBE Data CO2 (ppm)	CO (ppm)	NO (ppm)	HC (ppm)	H2O (ppm)	Ratio CO/CO2	Ratio NO/CO2	Ratio HC/CO2	Remote Sensor Data CO (%)	CO2 (%)	HC (%)	NO (%)	Ratio CO/CO2	Ratio NO/CO2	Ratio HC/CO2	OBE/Remote Sensor Ratio CO/CO2	Ratio NO/CO2	Ratio HC/CO2
1	123898	1207.30	1545.47	648.54	104900	0.00974	0.01247	0.00523	0.0800	14.93	0.0690	0.1600	0.00536	0.01072	0.00462	1.8185	1.1640	1.1326
2	121706	945.64	1978.94	761.07	103800	0.00777	0.01626	0.00625	0.0800	14.89	−0.0210	0.2760	0.00537	0.01854	−0.00141	1.4462	0.8772	−4.4339
3	123350	1087.85	1872.97	595.17	103800	0.00882	0.01518	0.00483	0.2000	14.77	0.2220	0.3170	0.01354	0.02146	0.01503	0.6513	0.7075	0.3210
4	121423	964.67	1869.36	708.12	99000	0.00794	0.01540	0.00583	0.1000	14.88	0.1980	0.2300	0.00672	0.01546	0.01331	1.1822	0.9960	0.4383
5	124468	1294.35	1758.40	676.90	108800	0.01040	0.01413	0.00544	0.1100	14.87	0.1800	0.2270	0.00740	0.01527	0.01210	1.4058	0.9254	0.4493
6	121457	972.46	1809.24	696.92	105400	0.00801	0.01490	0.00574	0.0900	14.89	0.2070	0.2350	0.00604	0.01578	0.01390	1.3246	0.9438	0.4127
7	122295	1081.44	1961.56	656.79	107400	0.00884	0.01604	0.00537	0.1000	14.88	0.1650	0.2510	0.00672	0.01687	0.01109	1.3158	0.9509	0.4843
8	122699	1063.05	1645.63	868.25	112200	0.00866	0.01341	0.00708	0.0700	14.90	−0.0780	0.2710	0.00470	0.01819	−0.00523	1.8442	0.7374	−1.3518
9	122113	1044.42	1751.94	583.54	101100	0.00855	0.01435	0.00478	0.0600	14.88	−0.1650	0.3270	0.00403	0.02198	−0.01109	2.1211	0.6529	−0.4310
10	122028	1057.15	1792.60	899.26	104300	0.00866	0.01469	0.00737	0.0600	14.92	−0.0270	0.2430	0.00402	0.01629	−0.00181	2.1542	0.9020	−4.0722
AVG	122544	1071.83	1798.61	709.46	105180	0.00874	0.01468	0.00579	0.0950	14.88	0.0750	0.2537	0.00639	0.01705	0.00505	1.5264	0.8857	−0.7051
%RSD	0.81	9.63	7.06	14.13	3.51	8.81	7.48	14.37	40.56	0.28	175.85	17.93	40.99	18.10	175.70	28.74	16.25	−267.12
11	128823	7517.22	1739.23	1043.67	114900	0.05835	0.01350	0.00810	0.8900	14.33	0.2850	0.1920	0.06211	0.01340	0.01989	0.9395	1.0076	0.4074
12	127433	9616.16	1814.23	897.46	111900	0.07546	0.01424	0.00704	0.9200	14.28	0.1290	0.2630	0.06443	0.01842	0.00903	1.1713	0.7730	0.7796
13	126912	8860.45	1661.90	1142.72	111100	0.06982	0.01309	0.00900	0.5800	14.54	0.1680	0.2420	0.03989	0.01664	0.01155	1.7502	0.7868	0.7793
14	126399	10818.39	1636.61	933.35	111200	0.08559	0.01295	0.00738	0.6600	14.51	0.1050	0.1740	0.04549	0.01199	0.00724	1.8817	1.0797	1.0204
15	127914	7643.57	1728.53	1014.82	108000	0.05976	0.01351	0.00793	0.6900	14.49	−0.0090	0.1990	0.04762	0.01373	−0.00062	1.2549	0.9840	−12.7731
16	127564	9730.20	1587.24	880.58	113900	0.07628	0.01244	0.00690	0.8400	14.35	−0.0900	0.2650	0.05854	0.01847	−0.00627	1.3031	0.6738	−1.1006
17	127507	8071.84	1391.28	1024.48	110200	0.06331	0.01091	0.00803	0.5600	14.57	0.1800	0.1930	0.03844	0.01325	0.01235	1.6471	0.8237	0.6504
18	129247	5182.46	1808.87	984.09	114700	0.04010	0.01400	0.00761	0.5500	14.56	0.1020	0.2300	0.03777	0.01580	0.00701	1.0615	0.8860	1.0869
19	127346	8643.53	2335.75	973.03	121200	0.06787	0.01834	0.00764	0.5800	14.54	0.3960	0.1830	0.03989	0.01259	0.02724	1.7015	1.4573	0.2806
20	127029	8163.19	1654.20	964.89	108200	0.06426	0.01302	0.00760	0.5600	14.56	0.1650	0.2150	0.03846	0.01477	0.01133	1.6708	0.8819	0.6703
AVG	127617	8424.70	1735.78	985.91	112530	0.06608	0.01360	0.00773	0.6830	14.47	0.1431	0.2156	0.04726	0.01490	0.00987	1.4382	0.9354	−0.8199
%RSD	0.64	17.30	13.32	7.35	3.28	17.75	13.28	7.33	20.36	0.72	90.41	14.47	21.15	14.87	90.55	21.71	22.31	−491.20
21	109623	1408.63	1136.54	2829.96	96300	0.01285	0.01037	0.02582	0.0600	14.93	0.1290	0.1830	0.00402	0.01226	0.00864	3.1975	0.8458	2.9878
22	122988	1432.64	702.26	575.57	102700	0.01165	0.00571	0.00468	0.0200	14.99	−0.1140	0.1480	0.00133	0.00987	−0.00761	8.7307	0.5783	−0.6154
23	120423	1205.22	1105.63	917.96	101500	0.01001	0.00918	0.00762	0.0900	14.87	0.1200	0.2770	0.00605	0.01863	0.00807	1.6536	0.4929	0.9446
24	123805	1532.82	733.67	591.49	108100	0.01238	0.00593	0.00478	0.0100	14.99	−0.0240	0.1540	0.00067	0.01027	−0.00160	18.5590	0.5768	−2.9840
25	118772	1232.66	1160.73	1083.50	102300	0.01038	0.00977	0.00912	0.0600	14.90	−0.0570	0.2760	0.00403	0.01852	−0.00383	2.5773	0.5276	−2.3847
26	119270	1519.83	807.95	1338.86	102900	0.01274	0.00677	0.01123	0.0100	14.95	−0.0030	0.2340	0.00067	0.01565	−0.00020	19.0504	0.4328	−55.9402
AVG	119147	1388.63	941.13	1222.89	102300	0.01167	0.00796	0.01054	0.0417	14.94	0.0085	0.2120	0.00279	0.01420	0.00058	8.9614	0.5757	−9.6653
%RSD	3.89	9.22	20.86	62.69	3.36	9.57	23.62	68.40	72.55	0.30	1046.08	25.19	72.76	25.44	1027.49	81.66	22.71	−215.11
27	124689	1227.40	1552.33	468.64	106000	0.00984	0.01245	0.00376	0.1500	14.93	0.0510	0.0440	0.01005	0.00295	0.00342	0.9798	4.2244	1.1003
28	120651	1056.44	1711.81	846.33	101400	0.00876	0.01419	0.00701	0.1300	14.96	0.1500	−0.0100	0.00869	−0.00067	0.01003	1.0076	−21.2254	0.6996
29	122778	1125.89	1864.70	503.17	105600	0.00917	0.01519	0.00410	0.1200	14.92	−0.2910	0.1550	0.00804	0.01039	−0.01950	1.1402	1.4619	−0.2101
30	120969	1108.29	1732.91	873.39	100300	0.00916	0.01432	0.00722	0.1200	14.94	0.0750	0.0700	0.00803	0.00469	0.00502	1.1405	3.0569	1.438
31	122938	1168.82	1812.96	544.08	106400	0.00951	0.01475	0.00443	0.1400	14.89	0.1410	0.1420	0.00940	0.00954	0.00947	1.0112	1.5464	0.4674
32	119756	1239.56	1783.22	1280.74	100200	0.01035	0.01489	0.01069	0.2400	14.78	0.5220	0.1950	0.01624	0.01319	0.03532	0.6374	1.1286	0.3028
33	121347	1034.28	1757.83	749.51	109200	0.00852	0.01449	0.00618	0.0900	14.99	0.0780	0.0030	0.00600	0.00020	0.00520	1.4196	72.3817	1.1870
34	122135	995.18	1440.39	575.27	100100	0.00815	0.01179	0.00471	0.0900	15.00	0.0390	−0.0020	0.00600	−0.00013	0.00260	1.3580	−88.4508	1.8116
35	122118	1090.96	1653.56	465.29	102400	0.00893	0.01354	0.00381	0.1300	14.91	0.1800	0.1190	0.00872	0.00798	0.01207	1.0246	1.6966	0.3156
36	122409	1107.22	1809.58	490.13	107100	0.00905	0.01478	0.00400										
AVG	121981	1115.40	1711.93	679.66	103870	0.00914	0.01404	0.00559	0.1344	14.92	0.1050	0.0796	0.0090	0.0053	0.0071	1.1045	−1.0255	0.7589
%RSD	1.08	6.72	7.23	36.59	3.07	6.61	7.55	37.72	31.19	0.41	187.42	90.22	31.72	90.38	187.70	19.84	14.27	116.95

APPENDIX 1: AEROSTAR AND REMOTE SENSOR DATA ACQUIRED AT THE DEARBORN PROVING GROUNDS

	Aerostar OBE Data								Remote Sensor Data							OBE/Remote Sensor		
Trial No.	CO2 (ppm)	CO (ppm)	NO (ppm)	HC (ppm)	H2O (ppm)	Ratio CO/CO2	Ratio NO/CO2	Ratio HC/CO2	CO (%)	CO2 (%)	HC (%)	NO (%)	Ratio CO/CO2	Ratio NO/CO2	Ratio HC/CO2	Ratio CO/CO2	Ratio NO/CO2	Ratio HC/CO2
37	122080	1030.96	1889.18	720.64	109000	0.00844	0.01547	0.00590	0.0700	14.97	−0.1140	0.0940	0.00468	0.00628	−0.00762	1.8060	2.4645	−0.7752
38	120700	968.33	1995.80	541.82	106200	0.00802	0.01654	0.00449	0.1400	14.90	0.2820	0.1010	0.00940	0.00678	0.01893	0.8538	2.4394	0.2372
39	121096	962.49	2155.09	582.44	104300	0.00795	0.01780	0.00481	0.2500	14.76	0.6720	0.1980	0.01694	0.01341	0.04553	0.4693	1.3266	0.1056
40	122664	1119.88	1723.63	818.35	109900	0.00913	0.01405	0.00667	0.0800	14.97	−0.0510	0.0830	0.00534	0.00554	−0.00341	1.7084	2.5344	−1.9583
AVG	121635	1020.41	1940.93	665.81	107350	0.00839	0.01596	0.00547	0.1350	14.90	0.1973	0.1190	0.00909	0.00800	0.01336	1.2094	2.1912	−0.5977
%RSD	0.64	6.21	8.10	16.56	2.08	5.59	8.62	15.91	53.03	0.58	158.52	38.71	53.68	39.41	158.22	46.76	22.84	−146.69
41	128130	6028.29	2045.15	666.70	112600	0.04705	0.01596	0.00520	0.6600	14.48	0.3180	0.2220	0.04558	0.01533	0.02196	1.0322	1.0411	0.2369
42	128044	6009.02	1923.45	942.35	113700	0.04693	0.01502	0.00736	0.5000	14.60	0.1320	0.2410	0.03425	0.01651	0.00904	1.3703	0.9100	0.8140
43	127797	5954.07	1838.03	667.95	106700	0.04659	0.01438	0.00523	0.7500	14.45	0.5460	0.0970	0.05190	0.00671	0.03779	0.8976	2.1425	0.1383
44	127936	5705.77	1791.94	968.45	111300	0.04460	0.01401	0.00757	0.4900	14.63	−0.0210	0.1850	0.03349	0.01265	−0.0014	1.3316	1.1077	−5.2736
45	127400	7450.37	1650.10	1006.97	113100	0.05848	0.01295	0.00790	0.5900	14.60	0.1290	0.0860	0.04041	0.00589	0.00884	1.4471	2.1989	0.8946
AVG	127861	6229.50	1849.73	850.48	111480	0.04873	0.01446	0.00665	0.5980	14.55	0.2208	0.1662	0.04113	0.01142	0.01524	1.2158	1.4800	−0.6380
%RSD	0.20	9.97	7.13	17.75	2.26	10.17	6.95	17.84	16.43	0.50	88.28	38.32	16.92	38.26	88.58	17.48	38.36	−366.37
46	128388	6011.88	1701.84	902.76	104200	0.04683	0.01326	0.00703	0.3200	14.74	0.2280	0.1850	0.02171	0.01255	0.01547	2.1569	1.0561	0.4546
47	128279	6621.17	2361.65	846.25	107400	0.05162	0.01841	0.00660	0.4800	14.60	0.2970	0.2310	0.03288	0.01582	0.02034	1.5700	1.1636	0.3243
48	127155	6971.19	1903.96	931.09	110800	0.05482	0.01497	0.00732	0.4600	14.66	0.0000	0.2020	0.03138	0.01378	0.00000	1.7472	1.0867	
49	128064	6891.63	1707.71	977.91	112800	0.05381	0.01333	0.00764	0.6200	14.54	−0.1380	0.2070	0.04264	0.01424	−0.00949	1.2620	0.9367	−0.8046
50	125758	10101.91	1347.14	1034.71	112300	0.08033	0.01071	0.00823	0.5000	14.64	0.4170	0.1060	0.03415	0.00724	0.02848	2.3520	1.4795	0.2889
AVG	127529	7319.56	1804.46	938.54	109500	0.05748	0.01414	0.00736	0.4760	14.64	0.1608	0.1862	0.03255	0.01273	0.01096	1.8176	1.1445	0.0658
%RSD	0.77	19.56	18.37	6.85	2.97	20.44	17.93	7.49	20.13	0.45	125.57	22.94	20.53	23.07	126.01	21.67	15.96	769.48
51	121746	18835.78	1465.88	1010.36	107500	0.15471	0.01204	0.00830	1.9400	13.62	−0.2370	0.0000	0.14244	0.00000	−0.01740	1.0862	UD	−0.4769
52	122154	17500.81	1342.45	1257.36	111500	0.14327	0.01099	0.01029	1.6800	13.79	0.5940	0.0940	0.12183	0.00682	0.04307	1.1760	1.6122	0.2390
53	120922	19818.48	1538.41	1274.21	113000	0.16390	0.01272	0.01054	1.9400	13.60	0.3600	0.1250	0.14265	0.00919	0.02647	1.1490	1.3842	0.3981
54	120932	18225.76	1377.58	1336.88	110100	0.15071	0.01139	0.01105	1.4700	13.95	0.2610	0.1110	0.10538	0.00796	0.01871	1.4302	1.4316	0.5909
AVG	121438	18595.21	1431.08	1219.70	110525	0.15315	0.01179	0.01005	1.7575	13.74	0.2445	0.0825	0.12807	0.00599	0.01771	1.2103	1.1070	0.1878
%RSD	0.44	4.57	5.35	10.20	1.83	4.86	5.58	10.40	11.21	1.03	123.99	59.25	12.18	59.41	124.77	10.83	58.24	214.89