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EVALUATION OF A REMOTE SENSOR FOR MOBILE SOURCE CO EMISSIONS

by

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CR-815778-01-0

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16. ABSTRACT

Carbon monoxide (CO) emission measurements of thousands of vehicles per day are possible with a recently evaluated remote sensor, developed at the University of Denver. Funded by the Environmental Monitoring Systems Laboratory - Las Vegas (EMSL-LV) Innovative Research Program, the evaluation has demonstrated the comparability of volume concentration measurements made by this method with traditional emission monitoring instrumentation. Measurements are made unobtrusively as vehicles pass through an infrared light beam directed across one traffic lane about 25 centimeters above the pavement. A video camera records the vehicle registration number of each vehicle as its CO emissions are measured so that characteristics of individual vehicles and vehicle fleet categories can be associated with each measurement. Determining appropriate applications and monitoring protocols for this technology is the second phase of this Innovative Research Project. Similar remote sensing technology for monitoring mobile hydrocarbon and nitrogen oxide emissions can be developed to address the urban ozone non-attainment problem.

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Foreword

Protection of the environment requires effective regulatory actions which are based on sound technical and scientific information. This information must include the quantitative description of pollutant sources. Because of the complexities involved, assessment of specific pollutants in the environment requires a quantitative approach. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound monitoring data base for exposure assessment through programs designed to

- o develop and optimize systems and strategies for monitoring pollutants and their impact on the environment
- o demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs.

This report presents test results of a new system used to remotely monitor the carbon monoxide and carbon dioxide emissions from on-road motor vehicles. In less than one second, a snapshot of the percent carbon monoxide emissions of a passing vehicle can be determined, along with a video image of the vehicle's license plate. Through the use of such a device, it would be possible to obtain large data bases of actual on-road vehicle emissions.

Environmental Monitoring and Support Laboratory
Las Vegas, Nevada.

Abstract

With previous support from the Colorado Office of Energy Conservation, the University of Denver (DU) has developed an infrared remote monitoring system for automobile carbon monoxide (CO) exhaust emissions which has been given the acronym FEAT (Fuel Efficiency Automobile Test). The purpose of this EPA-supported cooperative agreement with the University of Denver was to detail the theoretical operation of the system, to conduct verification tests of both the equations and the remote sensor, and to determine avenues for future research.

The FEAT system measures the CO/CO_2 ratio (Q) in a passing vehicle in 0.7 seconds. The Q values can be used directly as a measure of emissions quality, but are more commonly converted to other emissions or fuel efficiency parameters (such as effective air/fuel ratios, grams CO/gallon emissions, and the exhaust %CO and $\%CO_2$ by volume) by the use of simple equations. In addition to emissions information, the FEAT supplies a video image of the license plate of the passing vehicle; if access to vehicle registrations is obtained, this feature can be used to better characterize a local fleet or to notify the owners of high emitting vehicles.

The FEAT equations are theoretically sound and are generally applicable (i.e., not unique to the FEAT system). In intercomparison tests, FEAT measurement values compared very well to laboratory measurement values; when the FEAT values are adjusted for calibration differences, regression analysis yields a slope of 0.99, with a correlation coefficient (r) of 0.99 and a standard deviation of 0.17. The useful analytical range of the FEAT, in terms of %CO, is from 0 - 16% CO; absolute precision of repeat measurements is about ± 0.2% CO at low levels and ± 0.3% CO at higher levels. Relative error of the system is typically ± 5% of the observed reading.

Future research topics include studies to characterize the agreement between two FEAT instruments, investigations of how instantaneous emissions measurements correlate to conventional methods of emission determination, the effect of sample site on emission variability, and development of procedures for implementation of field applications (i.e., gross emitter detection and fleet monitoring). FEAT may represent a practical approach for the collection of on-road mobile emissions data which can be used to direct resources to that small fraction of vehicles that are responsible for most of the mobile source pollutants. As such, this technology may be the key element for the establishment of a series of cost-efficient pollution prevention activities.

Contents

Figures

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Abbreviations and Symbols

A	-- ampere
ADC	-- analog-to-digital converter
A/F	-- air-to-fuel ratio
C/H	-- carbon-to-hydrogen ratio
CO	-- carbon monoxide
CO/REF	-- ratio of carbon monoxide signal to reference signal
CO_2	-- carbon dioxide
CVS	-- constant volume sampler
DU	-- University of Denver
EPA	-- Environmental Protection Agency
ETC	-- Environmental Testing Corportation
FEAT	-- Fuel Efficiency Automobile Test
FMVCP	-- Federal Motor Vehicle Control Program
FTP	-- Federal Testing Procedure
GM CO/GAL	-- grams carbon monoxide per gallon
HC	-- hydrocarbons
I/M	-- inspection and maintenance
IR	-- infrared
MPG	-- miles per gallon
MPH	-- miles per hour
NAAQS	-- National Ambient Air Quality Standards
NDIR	-- non-dispersive infrared
NO_x	-- nitrogen oxides ($NO + NO_2$)
Q	-- carbon monoxide to carbon dioxide ratio
Q/A	-- quality assurance
REF	-- reference channel
VMT	-- vehicle miles travelled
XCL	-- exceeds confidence limits (error code)

Metric conversion Table.

Imperial Units	Metric Units
1 U.S. Gallon (Gal.)	3.785 Liters (l)
1 Mile (Mi.)	1.609 Kilometers (km)

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The authors wish to acknowledge Jim Bean, Paul Guenther, and Ian Stedman for their help in completing this work. We also wish to thank the Illinois Department of Energy and Natural Resources, the City of Colorado Springs, National Science Foundation, Amax Foundation and the University of Denver for the initial support that made this EPA-funded program successful. The constant communication with Marc Pitchford, and the oversight of the advisory committee were also important to the successful outcome of this project. Finally, we greatly appreciate the time and effort expended by Brian Johnson in editing the manuscript.

I. INTRODUCTION

With previous support from the Colorado Office of Energy Conservation, the University of Denver (DU) has developed an infrared remote monitoring system for automobile carbon monoxide (CO) exhaust emissions. The University of Denver CO remote sensor has been given the acronym FEAT for Fuel Efficiency Automobile Test, because significant fuel economy results if rich-burning (high CO) vehicles are tuned to a more stoichiometric (and more efficient) air-to-fuel (A/F) ratio.

This report describes a three phase evaluation of the FEAT, funded by EPA under cooperative agreement # CR-815778-01-0. The first phase was to describe the system and detail all the mathematical procedures which are used to convert the ratio of CO/CO_2 (as determined by the FEAT) to measures of vehicle CO emission (e.g., exhaust %CO and gm CO/gallon[1] of fuel consumed). The second phase of this program was to obtain some real-time emissions data from the literature and demonstrate that the FEAT equations hold when applied to data sets other than those generated by the remote sensor. The third phase was to compare FEAT measurements of vehicle emissions to those of laboratory-grade instruments.

Sections II and III describe the FEAT hardware and software, system calibration, and the measurement of CO/CO_2 ratios. Section IV summarizes the relevant chemistry of automobile exhaust which allows the calculation of other vehicle parameters. Sections V and VI discuss the intercomparison studies between FEAT and conventional emissions monitors at a commercial dynamometer facility. The important results of the study are summarized in Section VII, and future applications are discussed in Section VIII.

II. INSTRUMENT OVERVIEW AND MAJOR COMPONENTS

In this section, the general operating principles of the FEAT device are discussed, followed by more detailed descriptions of the important subsystems.

Overview

The FEAT system is based on the principle of infrared (IR) absorption, and is optically identical to other such monitors. The intensity of IR radiation at a selected

[1] A metric conversion chart is located with the list of abbreviations on page viii. Gallons and miles were used because they are the standard units, in the U.S., for measuring fuel volume and distance traveled with respect to motor vehicles.

wavelength is reduced by an amount which is a function of the concentration of the species which absorbs at that wavelength, and of the path length between the source and detector. Detectors convert the incident IR radiation to a voltage signal, and a computer determines the change in concentration corresponding to a measured change in voltage. (The calibration between change in voltage and change in concentration is pre-determined in the laboratory, and is adjusted for field settings by a field calibration.)

The computer determines the total amount of CO and CO_2 observed in a six to twelve-meter path. The absolute amounts observed are not used except to ensure that adequate exhaust was detected. The fundamental parameter derived from the signals is the CO/CO_2 ratio, which is called Q. Once Q has been determined and a value for the carbon/hydrogen ratio (C/H) supplied, the combustion equations can be solved for many of the vehicle operation parameters. Parameters which can be derived include the effective air/fuel ratio (A/F), the emissions of CO in grams per gallon of fuel (gm CO/gal), and the %CO which would be measured were the vehicle equipped with a conventional exhaust-measuring analyzer and a tailpipe probe. Figure 1 illustrates the basic components of the FEAT CO remote sensor.

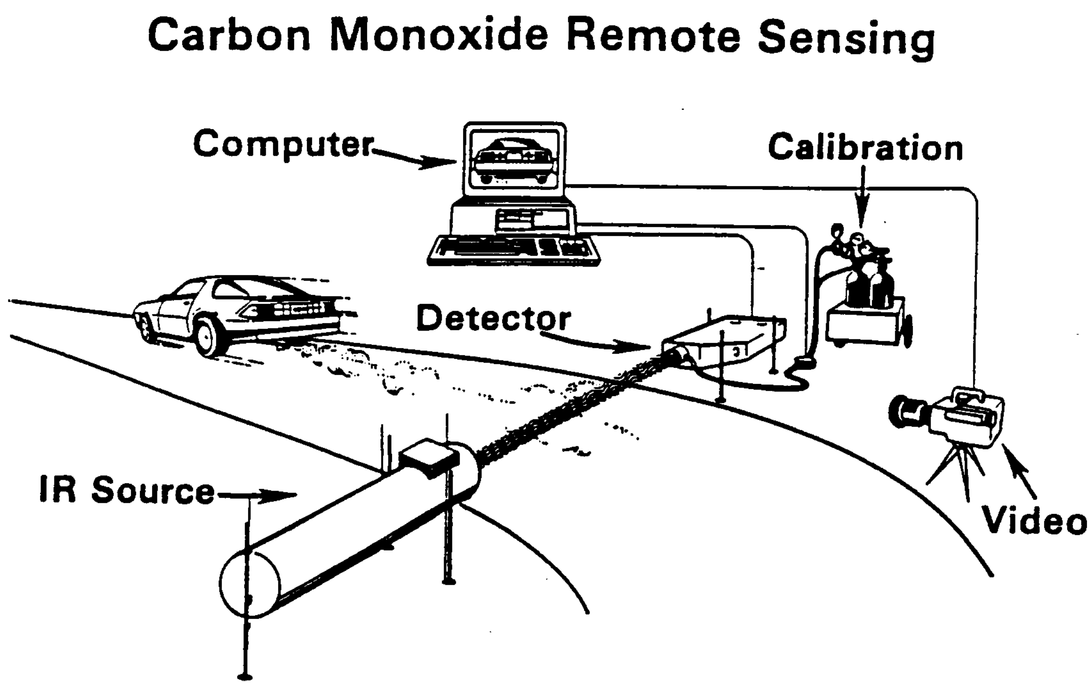

Figure 1 Schematic diagram of the DU CO remote sensor.

<u>Instrument components</u>

The FEAT instrument is comprised of 4 major parts: the IR radiation source, the detector subsystem, the computer, and the video camera. An interface (essentially a fifth component) was developed expressly for this study to allow FEAT to measure the emissions from stationary vehicles.

The IR radiation source consists of a commercially available silicon nitride gas drier igniter. When energized with 3 A of 110-V 60-Hz electricity, the source temperature increases to a stable value of 1,400°C. The IR radiation emitted by this source is collimated by a gold plated mirror (f4, 6" diameter) into a parallel beam.

The detector subsystem has been thoroughly described in the literature (1). Briefly, it consists of two liquid-nitrogen-cooled indium antimonide photovoltaic IR detectors equipped with interference filters at 4.6 and 4.3 micron wavelengths (for CO and CO_2, respectively). The internal optics include a germanium beam splitter, a sapphire-windowed rotating gas filter and several focusing elements. A 10-cm tube in front of the focussing lens serves as a chamber into which puffs of calibration gas are introduced by means of a computer-controlled solenoid valve. Internal electronics amplify the signals to between one and ten volts.

The analog signals are digitized at 30 kHz by means of an analog-to-digital convertor (ADC); the voltages obtained for a typical FEAT measurement are plotted in Figure 2a. These digital signals, modulated by the rotating gas filter wheel, are computer

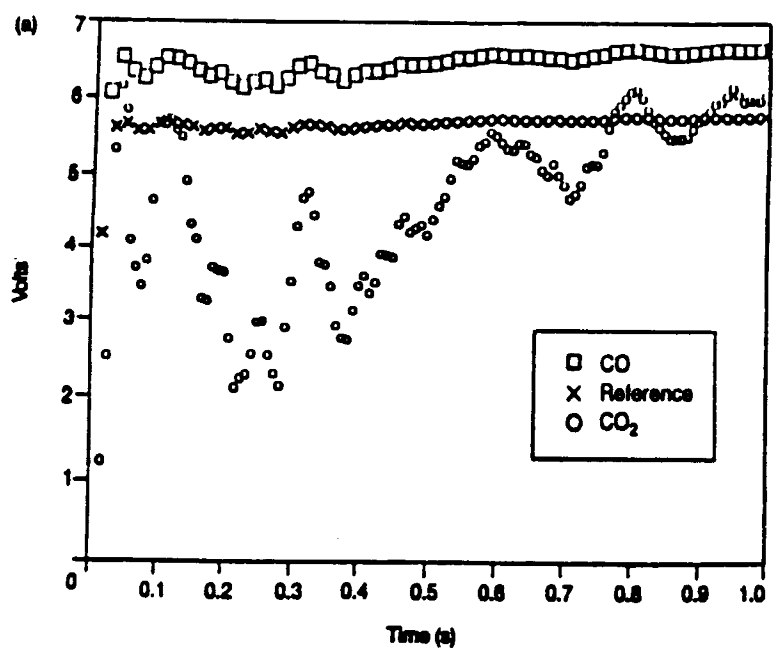

Figure 2 (a) Data from the remote sensor for a 1983 Oldsmobile at 20 mph

analyzed and converted to CO and CO_2 concentration values (Figure 2b). The CO concentration values are regressed against the CO_2 concentration values (Figure 2c) to

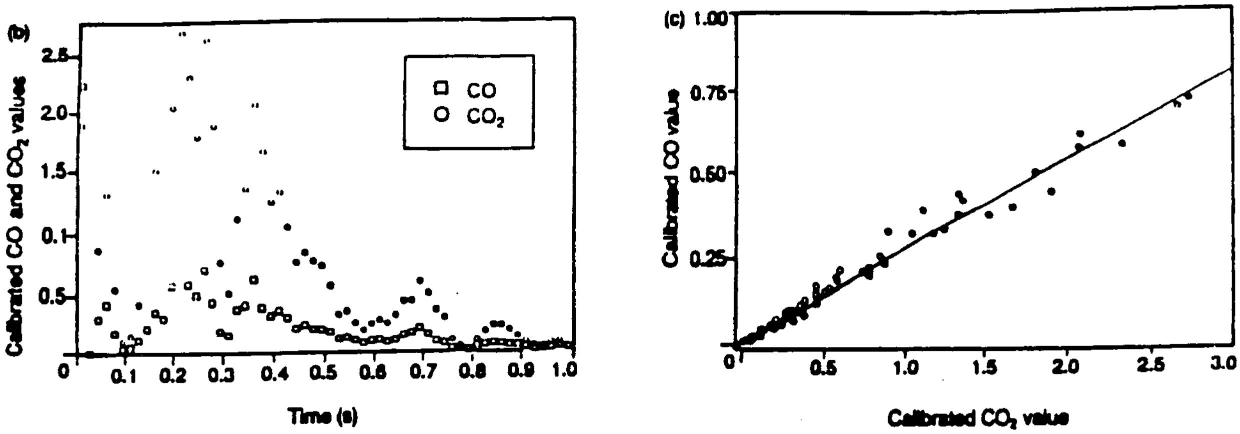

Figure 2 (b) raw data converted to calibrated CO and CO_2 values vs. time using a 10.16 cm calibration cell, and (c) the final CO/CO_2 correlation graph used to obtain unitless slope.

obtain the slope and the standard deviation of the slope. The slope, the CO/CO_2 ratio, is called Q, and the standard deviation of the slope is called σQ. Emission parameters (e.g., exhaust %CO) are calculated from Q, while σQ is used to evaluate the quality of the data.

The computer screen shows the derived %CO and $\%CO_2$ data from the most recent vehicle, together with the current voltage levels of the detectors, and a histogram showing the number of vehicles measured in each %CO emissions category since the operating program was last started. The computer also controls the video electronics when the video camera is in use, displays error messages and suggested corrections in the event of system malfunction, and, when calibration is needed, controls the calibration system. The computer automatically stores a database consisting of the date, time, and emissions for every time that the analysis program is triggered.

With the addition of a video camera and some copyrighted software, it is possible not only to measure the emissions of the passing vehicles, but also to record the image of each vehicle as it emerges from the FEAT beam position (see Figure 1). The computer freezes the image of the vehicle as it exits the beam region. After the exhaust emissions calculation is completed, the computer writes the date, time, vehicle number, CO and CO_2 emissions on the video screen together with the vehicle image. The video information is recorded on an S-VHS videotape. The total time from initiation of data analysis to display of the video image with emissions information is between 0.8 and 0.9 seconds.

One challenge of this project was to determine the emissions of a stationary vehicle with the FEAT unit. This capability was necessary to enable comparisons to be made to conventional emissions testing at a dynamometer facility (Section V). In order for these tests to be carried out, a device was required which would simulate the proper conditions under which the FEAT was designed to operate. The device needed to meet three criteria:

1) A blocked beam simulating the wheel or body of a passing vehicle. This signal is used to zero the voltages.

2) Reasonably clean air before the beam is blocked in order for the intensities to reach their normal span value (I_o).

3) A puff of exhaust gas whose concentration varies significantly during the half second after the beam is unblocked. This allows the FEAT unit to observe a variable exhaust gas signal, and thus obtain a reliable CO/CO_2 slope.

Incorporating these parameters into the device allows the same computer algorithms to be used in the intercomparison as are used in the highway measurements, an important component of the protocol for the comparison procedure (Appendix D).

A device called rotofeat was used for one day of testing. Although this device appeared to be very successful when tested at the University of Denver, the very high levels of ambient CO at the dynamometer facility contributed to unsatisfactory performance for high-emitting vehicles (see Section V).

The most successful interface used to date is shown in Figure 3. The goal of this device is to deliver a short (0.3 second) puff of exhaust to a tube in front of the FEAT unit; a fan then clears out the tube. Raw exhaust is delivered from the rear of the vehicle to the intake of a small diaphragm compressor pump; this pump increases the pressure in a stainless steel storage vessel. Exhaust and water leave the vessel through a bleed valve at the bottom, while a computer-actuated solenoid valve delivers a 0.3-second puff of exhaust every two seconds. The black rotating blade of a light chopper simulates a passing vehicle by blocking the beam, and starts the computer timing cycle for exhaust addition. Because of the dead volume of the tubing and storage vessel, there is a short time lag between tailpipe emission and measurement by the FEAT when using this interface.

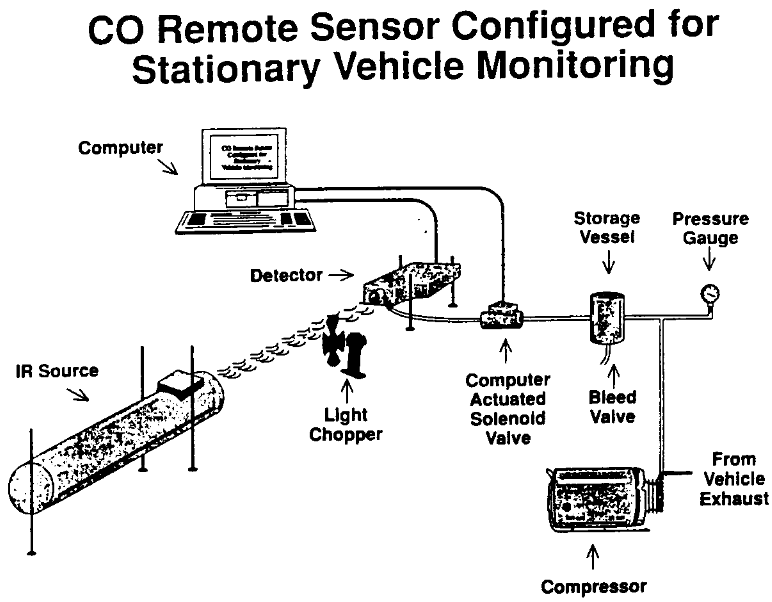

Figure 3 Schematic diagram of the interface enabling stationary vehicle exhaust to be measured with the FEAT detection system.

III. FEAT OPERATIONS

The basic instrument is designed to measure the CO to CO_2 ratio (Q) in the exhaust of any vehicle passing through an infrared light beam which is transmitted across a single lane of roadway. The infrared (IR) source sends a beam of radiation 25 cm above the road. This beam is picked up by the detector and split into the three wavelength channels: CO, CO_2, and reference. Data from all three channels are checked manually for adequate (1 to 9 volt) signals, which are then automatically fed to the computer for analysis. The complete computer data acquisition and processing cycle has been detailed in the literature (1). Calibration gases are used as a daily quality assurance check on the system.

Calibration

The fundamental infrared response of the three channels (i.e., reference, carbon monoxide and carbon dioxide) to known concentrations of CO and CO_2 is determined in the laboratory, and initial readings utilize this calibration. After setup at a given location, the instrument is also field calibrated. The system is zeroed by the simple expedient of the operator blocking the beam with a hand, followed by exhaling into the beam path. (Non-smoking human beings emit CO_2 and not CO, thus providing a conveniently available zero CO/CO_2 ratio.) Three certified gas cylinders of known values of Q are used to provide span readings. A puff of gas from the selected cylinder is sent to the calibration chamber on command from the computer, and a slope is derived from the calibration readings. Calibration cylinders (CO and CO_2 in nitrogen from Linde or Scientific Gas, Inc.) have a claimed traceable accuracy of $\pm 2\%$ by a gravimetric cylinder filling procedure. All the data are compared to spans from these cylinders. The spans are obtained on the same day and using the same hardware and software as the on-road measurements.

Operation: Error codes

The detectors are on-line constantly once they are turned on. The exhaust gas analysis routines are triggered by the beam being blocked (e.g., by a vehicle or pedestrian). If the beam is blocked and less than a preset minimum CO (0.04 atm cm) or CO_2 (0.01 atm cm) increase is observed after it becomes unblocked, the computer gives a 990 XCL (eXceeds Confidence Limits) error code. This code is generated by the wheels of large trucks or tractor trailers with elevated exhausts, pedestrians, etc.

If CO_2 and/or CO are observed, the computer plots Δ CO versus Δ CO_2 where Δ indicates the increase in CO or CO_2 above that measured in the air just in front of the vehicle. The least squares slope of the line is Q. The computer also calculates the standard deviation of the slope, σQ. If $Q <= 0.1$ (as is the case for most vehicles) and $\sigma Q > 0.02$, an XCL code of 991 arises; if Q is > 0.1 and $\sigma Q > 0.2*Q$, the same error code arises. The 991 code indicates a measurement beyond the required tolerance for precision.

If a vehicle is tailgated so closely that the half second of exhaust gas reading is interrupted, then the computer restarts the calculation but determines the emissions of the second vehicle using the air in front of the first vehicle as its reference.

In summary, 990 indicates no exhaust plume observed, while 991 indicates that a plume was observed but the derived CO/CO_2 ratio was too noisy to report with certainty. Under normal operating conditions, these codes are observed about 10% of the times that the beam is blocked. Rain and snow increase the rate at which confidence limits are exceeded.

System check

The check for normal operation after setup and calibration consists of observing the build up of the histogram of %CO emissions for approximately 100 passing vehicles. The system operates without manual intervention. When the video system is connected, there are startup adjustments to make. The camera is set at 1/1,000 sec in order to freeze the image, and the focus and zoom are set to optimally observe the license plate area on the vehicle. When these adjustments are made, the video tape is started and the operation is then fully automatic.

From the video tapes, license plate information may be entered into the computerized FEAT database of emissions values. Currently, this procedure is carried out manually. The license plate data are written onto a computer tape and submitted to the relevant state motor vehicle licensing department for determination of the make and model year of all the passing vehicles which are equipped with readable, in-state plates. From this information, statistics can be determined relative to the make, model year, etc. distribution both of the whole fleet and of the gross polluters. To speed up the slow process of manually reading the video tapes, two approaches are possible. The first is to record the video images digitally, then purchase or develop software to locate and read the plates automatically. The second is to purchase a commercially available (Perceptics Corp. Knoxville Tenn.) device which reads the image of the vehicle in real time, carries out the required pattern recognition, and returns the license plate data in real time to a computer.

IV. FEAT EQUATIONS: THEORY AND VERIFICATION

The first of the tasks in this project was to provide a detailed analysis of the equations which are used to interpret the FEAT data. In this report, all ratios are in molar units. This simplifies the chemistry calculations, because molar units are the natural units in which to study chemical reactions such as combustion. The CO/CO_2 ratio by moles is abbreviated as Q. Moles are also directly proportional to volumes at constant temperature and pressure; therefore, emissions percentages derived from Q (e.g. exhaust %CO; see below) are by volume.

A second goal was to prove that the validity of the FEAT equations is not dependent on or unique to the FEAT instrumentation. Exhaust data supplied by a U.S. automaker were analyzed using the FEAT equations; results were then compared to the original data.

Theory

While Q, the fundamental quantity obtained from a FEAT measurement, is very useful and has direct applications to emissions monitoring, it is desirable to have the ability to compare FEAT measurements to other emissions measurements. A number of different quantities can be derived from Q if the general combustion equation is known.

In the following text, the determination of exhaust percent carbon monoxide (%CO), weight of carbon monoxide in grams per gallon of fuel burned (gm CO/gallon), and effective air-to-fuel (A/F) ratio are described. Exhaust %CO is the quantity determined in standard inspection and maintenance (I/M) emission tests (e.g., tailpipe monitors), gm CO/gallon is the FEAT analog of gm CO/mile (used in FTP studies and computer models of regional emissions), and A/F is used by automotive engineers to determine engine condition.

It should be noted that Q, because it is a ratio, is a non-linear term. At increasing values of Q, the associated error bounds increase dramatically. This is not to imply that Q is a term which cannot be measured accurately or precisely, but that any term which tends to infinity at high CO will have error bounds which also approach infinity. This source of error is small, because large Q values are not encountered in emissions monitoring, and even for infinite values of Q, the exhaust %CO cannot exceed 22%.

The chemistry of motor vehicle exhaust is simplified by considering the engine and emission control systems as a simple combustion reaction chamber. Figure 4 shows a

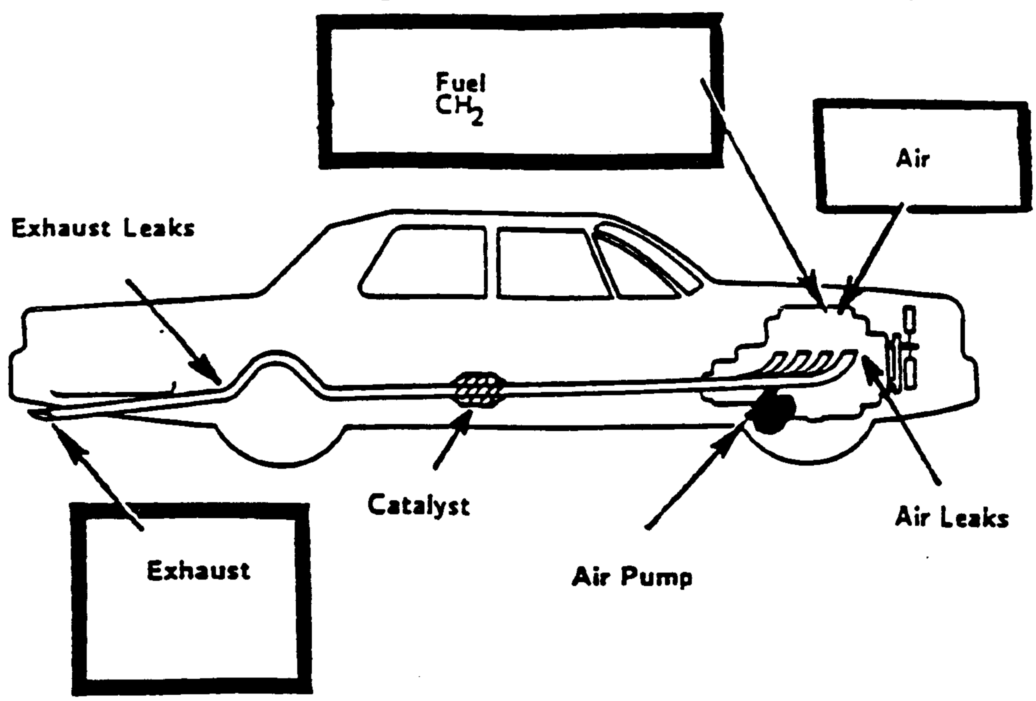

Figure 4 The only source of excess CO or CO_2 in the exhaust that is monitored by FEAT results from the combustion of the carbon in the fuel, either in the engine or on the catalyst.

schematic diagram of an automobile. An automobile can be considered as a device in which fuel containing carbon and hydrogen (formula CH_n) is burned with air (whose approximate formula for this purpose is given as $(0.21O_2 + 0.79N_2)$ in a combustion chamber to derive power. The products are sometimes further burned on a catalyst or in the exhaust system. However, all combustion processes (power or catalytic) are governed by the same combustion equation:

$$CH_n + m(0.21O_2 + 0.79N_2) \rightarrow \frac{n}{2}(H_2O) + aCO + bCO_2 + 0.79mN_2 \qquad [1]$$

Figure 5 illustrates the chemistry arising from equation 1, and shows that a vehicle burning fuel with too little air (rich combustion) makes up for the lack of air by not burning all the carbon in the fuel to CO_2. Some remains as CO. Any hydrogen in the

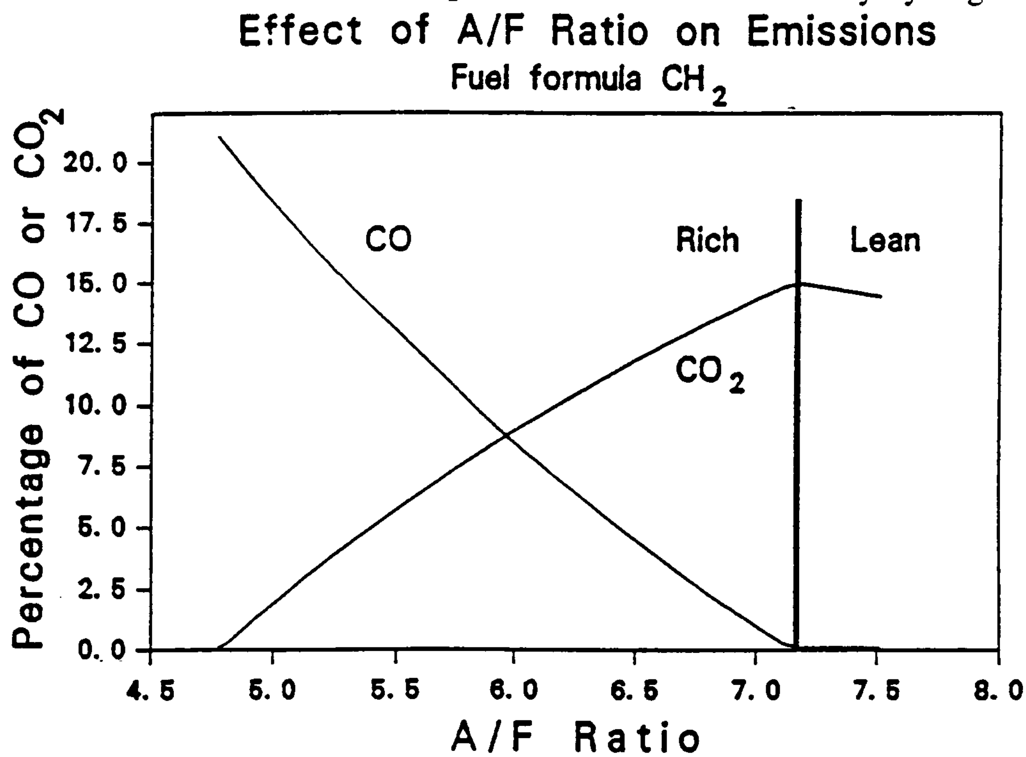

Figure 5 A gasoline engine combustion graph showing calculated CO and CO_2 emissions as a function of molar air-to-fuel ratio. The solid vertical line represents stoichiometry.

fuel is burned to water. The remaining oxygen is partitioned between CO and CO_2 according to Figure 5. Molar A/F ratios less than 4.5 (i.e., weight ratio of 9.3) are so rich that there is not enough oxygen even to burn the fuel to CO and H_2O. Combustion is so poor under these rich fuel conditions that vehicles cannot operate.

If the overall combustion process is complete, then all the fuel is burned to CO_2

and H_2O (i.e., a = 0, a/b = Q = 0). If the overall combustion process is not complete--that is, the engine is getting more fuel than the air can fully combust and is in a rich burning mode--then some of the carbon will appear as CO (i.e., a > 0, Q > 0). The remote sensor measures the increase in CO and CO_2 behind the vehicle compared to that in front of the same vehicle. Since the fuel is the only source of extra carbon either for CO_2 or CO, then a measure of Q amounts to a measure of the efficiency with which the overall combustion system of a car converts the fuel carbon into CO_2. In real exhaust, there are additional components, the most important of which are unburnt hydrocarbons and oxides of nitrogen. Although they are important air pollutants, both are at small enough levels that they do not significantly affect the equations for the major species CO and CO_2. It is possible to develop techniques to measure remotely both hydrocarbons (HC) and nitrogen oxides (NO_x) in addition to CO.

Table I shows that large values of Q can only be measured in the exhaust of a vehicle which has both a rich-burning engine and an incompletely effective emissions system. The ratio Q depends on the status of both the engine and the emissions system. Table I illustrates that, even without all the succeeding mathematical derivations, a remote sensor which can quickly and accurately measure Q can indicate the engine/emissions system status of a passing vehicle. Uncertainties in the fuel chemistry will not introduce errors into the remote determination of Q. If the purpose of a remote sensor is to detect the worst offenders, values of Q can be used directly.

Table I: Relation of Engine Status to CO/CO_2 ratio.

Table I		
Engine Status	**Emission System**	**Q**
Lean	Operational	0
Lean	Not Operational	0
Rich	Operational	0
Rich	Not Operational	>0 as high as 4 in extreme cases

The derived quantity reported most frequently for the FEAT is the dry, undiluted exhaust %CO. The equations used to derive exhaust %CO from Q assume that all oxygen is consumed by the fuel during the combustion process. In fact, however, most automobiles will entrain air into their exhaust systems due to the action of the air pump, thereby lowering the %CO and %CO_2 emitted from the tailpipe due to dilution. There will therefore be a discrepancy between FEAT values of %CO, and %CO as determined by a conventional tailpipe probe. This discrepancy can easily be remediated if percent oxygen data are available for the tailpipe emissions; all the tailpipe data are adjusted upwards by multiplying by the term [21/(21 - %O_2)]. If oxygen data are not available, the %CO values reported by the FEAT will exceed those measured by a tailpipe probe.

The equation used to derive %CO from the measured Q is:

$$\%CO = \frac{42Q}{2.79 + 2Q} \qquad [2]$$

Equation 2 (derived in Appendix A) is independent of the nature of the vehicle and of its emissions system. It is slightly dependent on the chemical nature of the fuel, but the relative error in the determination of %CO will be less than the relative error in the carbon/hydrogen ratio (C/H) assumed in the calculation. Gasoline is a mixture of many species including saturated hydrocarbons (for instance, hexane, C_6H_{14} with more than two hydrogens per carbon) and aromatic hydrocarbons (for instance, toluene, C_7H_8 with less than two hydrogens per carbon). The average comes out quite close to a ratio of two hydrogens per carbon (CH_2). Other calculations have used $CH_{1.85}$ as a representative fuel. If the exact C/H ratio of the fuel is known, this small error can be eliminated. Assuming a C/H ratio of 1:2 when 1:1.85 is correct will introduce a maximum error of 8% in the derived %CO, far less in most cases.

To derive from Q the vehicle emissions in gm/gallon of fuel burned, the combustion equations are solved as before. However, a small correction arising from tailpipe hydrocarbon emissions is required. An approximate equation totally neglecting hydrocarbon emissions is

$$gm\,CO/gallon = \frac{5300Q}{1 + Q} \qquad [3]$$

With a hydrocarbon correction factor based on correlation between measured tailpipe CO and HC, one obtains

$$gm\,CO/gallon = \frac{5650Q}{1 + 1.08Q} \qquad [4]$$

For normal values of Q, the differences between the two equations are small. If the ratio Q' (where Q' = CO/HC) is known or measured (as will be the case when an HC channel is incorporated into future models of the FEAT), a complete solution of the gm CO/gallon equation is possible. It takes the form

$$gm\,CO/gallon = \frac{5650Q}{1 + Q + \frac{Q}{Q'}} \qquad [5]$$

These equations are not new to FEAT and are all derivable directly from the published US EPA gas mileage equations (2). The calculations are detailed in Appendix A; it is shown that the error arising from total neglect of HC is « 6 percent for most vehicles.

Appendix A details the theory by which the effective instantaneous A/F ratio of the overall combustion (engine plus emissions system) can be determined from a remote sensing measurement of Q. Using CH_2 as the formula for "gasoline", the resulting equation has the simple form

$$Molar\ Air/Fuel = \frac{3 + 2Q}{0.42(1 + Q)} \qquad [6]$$

Appendix A shows that the A/F ratio is approximately proportional to 2 + n/2 where n is the number of hydrogens in the fuel. Thus for n values close to two (namely all normal gasolines), any uncertainty in the value assigned to n is halved when the A/F calculation is carried out. Thus, if the fuel is really $CH_{1.85}$, the error in instantaneous molar A/F calculated from FEAT data would be less than 4%.

Air-to-fuel ratio and fuel efficiency are directly related because the vehicle is getting the most energy out of its fuel only if just enough air is present to burn the fuel fully to CO_2 and H_2O. An approximate solution to the energy balance from the combustion equation [1] above indicates that the combustion efficiency is decreased by approximately twice the observed %CO. Thus a gross polluting vehicle measured at a Q = 1 will have a molar A/F of a little under 6, and a CO concentration of 8.8%. If this vehicle were tuned to have the necessary extra air, that is to the stoichiometry point, the combustion efficiency would improve by approximately 16%.

Verification: FEAT equation test

Because the combustion mechanism on a catalyst is fundamentally different from that in an engine, it was not obvious (a priori) that the FEAT equations would give accurate results in the situation where a catalyst was partially, but not completely, operational. Some data supplied by Chrysler Corp. were used to test the equations. Real time data from a malfunctioning vehicle were available from upstream and downstream of a catalyst. The catalyst was operating with 100% efficiency when the engine was emitting low-to-moderate CO levels, but when the engine emissions went up to 7% CO, the catalyst was only about 50% efficient.

The test consisted of taking the observed CO and CO_2 data, using the O_2 to correct the CO and CO_2 for dilution, calculating the CO/CO_2 ratio, and using the FEAT equations to obtain %CO and %CO_2 values for comparison with the original data. Figure 6 shows the results of the test. The lines are the predicted %CO based on the FEAT

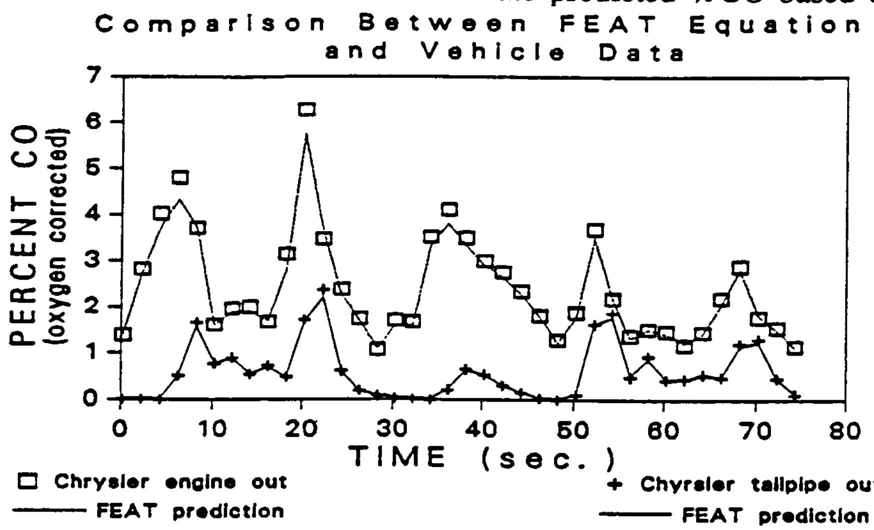

Figure 6 Chrysler data on a malfunctioning vehicle. Upper and lower lines are the FEAT equation prediction before and after the catalytic converter, respectively. Measured values are indicated by symbols.

equations and the measured CO/CO_2 ratio. The points are the measured %CO data.

The agreement between equation and data is excellent both upstream and downstream of the catalyst; minor differences noted at 3 peak concentrations may be due to a time lag between the CO and CO_2 monitors. These results suggest not only that the FEAT equations are valid independent of the FEAT instrumentation, but that the accuracy of a FEAT measurement would not be compromised by a malfunctioning catalyst.

V. COMPARISON OF FEAT TO CONVENTIONAL LABORATORY MONITORS

This section describes the two days of comparison tests. The original protocol (Appendix C) called for one day of testing, but, as previously mentioned (Section II), limitations of the rotofeat interface prompted a second day of testing with a new interface. A description of the protocol (i.e., with the necessary refinements) in the next paragraph is followed by descriptions of the test facilities, cross-calibration between FEAT and the laboratory monitors, and the data that was obtained.

Problems with the interface during the afternoon of the first sample day resulted in a necessary change in the protocol. The remaining comparisons were suspended until a new interface could be developed and tested. The new interface was then set up and cross-calibrated with the instruments at the facility; the FEAT was operated by the DU staff until they were confident that the FEAT system was performing properly. Non-DU staff then performed the intercomparison study (as specified in the protocol). Finally, a non-steady state test was performed at the end of the second day.

Testing was conducted at the Environmental Testing Corporation (ETC), a private automobile emissions test laboratory in the Denver area. The ETC staff carry out high altitude certification tests for several automobile manufacturers. The ETC laboratory is equipped with dynamometer facilities, constant volume sampling (CVS) dilution systems and a full suite of exhaust gas analytical instrumentation. The analyzers are calibrated by means of a large array of traceable gas standards. Laboratory information is provided in Appendix B.

A copy of the test protocols developed for this program is included in Appendix C. Briefly, the protocols consisted of two parts. Included in the first part was a suite of steady-state tests on several vehicles under various combinations of speed and load. These tests were to be performed blind, in that an EPA representative was to receive data from both DU and ETC for comparison. The second section was to try to determine real-time emissions from a cold-start vehicle using both systems, and to compare the data from both the ETC exhaust gas monitors, and the DU FEAT readings. This comparison was not to be carried out in a blind mode.

On arrival at ETC, the FEAT calibration gas cylinders (certified to $\pm$ 2%) were used to calibrate the FEAT unit. Three cylinders are normally used, with certified ratios and absolute values. The certificates read:

6.0% CO with 6.0% CO_2 balance nitrogen (i.e., Q = 1.00)

4.96% CO with 1% CO_2 (Q = 4.96),
1% CO with 12.1% CO_2 (Q = 0.083).

The FEAT system zero was checked by one of the non-smoking investigators breathing into the beam after it had been blocked by hand or by the rotating blade (Section IV). For the Q = 1.00 ratio cylinder calibration, Q was determined to be between 1.16 and 1.18. (As detailed in Section IV, the normal FEAT software collects data according to a previous laboratory calibration, then corrects the data from the field calibrations before reporting.) Therefore, it was anticipated that the FEAT readings would have to be adjusted downward by about 17% to be compatible with the dynamometer readings.

When testing the new interface on the second test day, initial ETC readings and the FEAT readings were very similar for the first test vehicle (both units registered Q = 0.77). This was not anticipated since, as noted above, the FEAT unit was reading about 17% high compared to the rated values of the calibration cylinders. Therefore, the ETC intake system was presented with gas directly from the FEAT calibration cylinders. The system correctly read zero percent oxygen, indicating no leaks, but the %CO and %CO_2 values did not agree with the manufacturers certificates (except for the Q = 0.083 cylinder manufactured by Scott). On the Linde certified 6.0% CO/ 6.0% CO_2 cylinder, ETC read 6.5% CO and 5.86% CO_2 for a ratio of 1.11. On the Linde certified 4.96% CO/ 1.00% CO_2 cylinder, ETC read 5.3% CO and 0.85% CO_2 for a CO/CO_2 ratio of 6.23 instead of 4.96.

On the basis of the results for the "Q = 1.00" standard, the discrepancy between FEAT and ETC would be expected to be about 5% (i.e., 100*[1.17-1.11]/1.11) by which the FEAT readings should be increased. Note that this correction is in addition to the dilution adjustment discussed earlier (Section IV; Determination of exhaust %CO). For comparisons with the FEAT data, the ETC data reported in this document were adjusted for dilution effects when O_2 concentrations were available, but no calibration adjustment was performed on either of the data sets.

<u>November 1, 1989 ETC Tests</u>

FEAT was set up in the parking lot to the south of the ETC building; it was separated by a wall from the dynamometer facility inside. The CVS vents exhaust output through the wall about 20m from the FEAT beam. A large tube was used to duct the CVS vent to the rotofeat interface used in the first tests.

Several vehicles were tested on November 1, 1989 as described in the protocols. The vehicle used to set up the system was a 1977 VW 2.0-L fuel- injected bus. This vehicle proved to have exhaust leaks and was not welcome in the facility after the initial setup and one preliminary set of readings. The other vehicles tested were a fuel injected 1987 Toyota Tercel, a 1986 Oldsmobile Cutlass, a 1988 Ford Thunderbird and a 1972 Chevrolet pickup. The vehicles were tested at 10, 20, 35 and 50 mph with two loads, their normal FTP load, and triple their FTP load.

It was apparent that the rotofeat interface was causing considerably more noise, and thus higher XCL rate, than when it had been tested at DU (or than the FEAT unit alone exhibits in normal highway use). As discussed elsewhere (Section II), only data from the clean vehicles passed a criterion that the ratio of CO signal to reference signal (CO/REF) was not more than a factor of two above the normal operating value. This allowed for valid data from all the vehicles except the 1972 Chevrolet pickup (a total of 72 data points). Appendix D contains the data sheets for each of these vehicles--the 1972 Chevrolet pickup is therefore not listed for reasons given above.

November 15, 1989 ETC Tests

These tests consisted of four parts: set up of the new interface, cross-calibration of FEAT and dynamometer measurements (as detailed above), standard intercomparison tests, and a non-steady state comparison test. To initiate use of the new interface, the FEAT system was set up as before except that an attempt was made to ensure that the CVS exhaust did not come near to the FEAT beam. Raw exhaust was fed to FEAT from a pipe hooked to the vehicle exhaust system next to the ETC raw-exhaust takeoff. This pipe was lead out through the wall via a ventilator opening. The new interface unit described earlier, and shown diagrammatically in Figure 3, was checked at the University of Denver, then tested at ETC on November 15, 1989.

For the standard intercomparison tests, vehicles were tested in the same manner as for the November 1 tests. To ensure that the new interface was working properly, a supervised pretest was performed for the first 160 FEAT data points. Personnel from the Colorado State Department of Health, High Altitude Inspection Laboratory, then performed a blind intercomparison, obtaining 116 FEAT data points.

One of the important parts of the protocol was to compare %CO measurements at the dynamometer facility to those of the FEAT unit during a non-steady state test; the cold start 505 test, a standard FTP test cycle, was chosen for this purpose. This procedure involves a 505-second cycle whereby a previously unstarted vehicle (usually allowed to thermally equilibrate with ambient air) is started and run through established RPM and load factors (i.e., according to FTP). Since the %CO changes rapidly during this test, it affords an excellent means by which to evaluate the ability of the FEAT unit to respond to changing concentrations of emissions.

To perform the cold start 505, one of the Colorado State test laboratory employees offered his personal vehicle, a 1983 Dodge Ram 50 sport subcompact pickup with a 2.6-L carburetted engine (Mitsubishi), for the test. After "cold soaking" outside at temperatures near 5° C. for nine hours, the vehicle was pushed onto the rollers and cold started. The FEAT unit was started 16 seconds into the cycle and read over 16% CO. Due to the impracticality of changing scale readings in the middle of a run, the ETC data were not available for the first 120 seconds of the run until the signal returned from off scale readings (i.e., to less than 10% CO).

VI. TEST RESULTS AND CONCLUSIONS

Data Description

On the first test date, ETC reported approximately 360 ten-second average readings of raw exhaust for %CO, %CO_2, and %O_2 for the five vehicles, as well as vehicle speed. FEAT reported about 1,500 readings of the CO/CO_2 ratio. For the blind intercomparison, speed, load, and vehicle were also recorded. FEAT data from the first test were excluded when the CO/REF ratio was outside the factor of two limit. Therefore, all the data were included except for those obtained when the vehicles were emitting more than 3% CO. About two thirds of the total data could be used. The valid data are summarized in Appendix D.

For the second test date, FEAT reported 116 measurements to be averaged into the blind intercomparison, and 160 measurements to be used for the pretest data. Both of these data sets were averaged to obtain eleven data points for the eleven vehicle settings. These points were compared to the average of two steady ETC readings of CO, CO_2 and O_2 in each case.

In the cold start 505 intercomparison, there are in principle 235 data points from FEAT compared to 235 from ETC. For this test, however, it was not possible to reprogram the ETC system to obtain the concurrent oxygen data. As mentioned in Section V, the ETC data was not available until about 120 seconds into the run, when it returned from off scale readings. The ETC printout was digitized by hand at the University of Denver Department of Geography to provide the data points.

Intercomparisons

Table II shows a comparison of FEAT and ETC data from one typical clean vehicle test from the first set of runs on November 1, 1989. Two steady state loads and four speeds per load are shown. ETC reported three, ten-second averages under each speed/load condition. Because of the high signal-to-noise levels, resulting in more frequent XCL error codes, FEAT reported between four and seven points which were used to generate each ten-second average. In all, 140 FEAT data points were used to create this table. On average, ETC readings were larger than FEAT readings by 0.11 ± 0.14 %CO, which is not significant. Individual FEAT data points showed a standard deviation of 0.16% CO.

Figure 7 shows the data on the same graph from both the blind comparisons (i.e.,

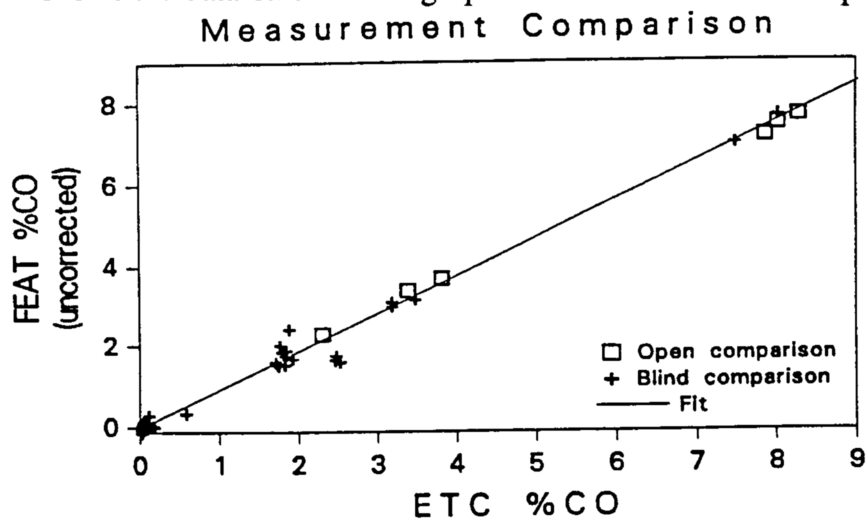

Figure 7 Uncorrected FEAT readings plotted against ETC readings. Blind comparisons from 11/1/89 and 11/15/89. Open comparison data from 11/15/89 is dilution corrected. All data not corrected for calibration cylinder discrepancies.

both test dates) and from the open (i.e., pretest) comparison on November 15 using the new interface. Oxygen dilution data were unavailable for the November 1 data; therefore, the ETC %CO values are not adjusted for dilution. Note that measurements close to zero require no adjustment even if oxygen were present, due to the small absolute magnitude of the adjustment. The appropriate dilution and calibration adjustments are discussed in Sections IV and V, respectively. A straight line regression was carried out on the data displayed in Figure 7 and Table III, resulting in a slope of 0.94 and an intercept of 0.009. A standard deviation of the regression of 0.17 and an R^2 of 0.99 were obtained using a standard statistical package. If FEAT data were calibration adjusted to be comparable to ETC data (i.e., adjusted upwards 5% as detailed in Section V), the slope would be even closer to unity; R^2 and the intercept would remain essentially unchanged.

Concerning the blind intercomparison data from November 15, O_2 and CO_2 data were not available for the first reading, but were for all subsequent readings. For each

Table II: Dynamometer percent CO data from FEAT and ETC for a 1986 Oldsmobile Cutlass

Table II							
	1st 10s average		2nd 10s average		3rd 10s average		All data
Speed	FEAT	ETC	FEAT	ETC	FEAT	ETC	$\|\overline{FEAT}-\overline{ETC}\|$
10 MPH	-0.02	0.005	-0.02	0.005	0.06	0.005	0.002
20 MPH	0.08	0.005	-0.03	0.005	-0.03	0.005	0.002
35 MPH	0.07	0.02	-0.04	0.01	0.01	0.05	0.013
50 MPH	-0.02	0.08	-0.04	0.06	-0.02	0.03	0.083

Triple Load							
	1st 10s average		2nd 10s average		3rd 10s average		All data
Speed	FEAT	ETC	FEAT	ETC	FEAT	ETC	$\|\overline{FEAT}-\overline{ETC}\|$
10 MPH	-0.04	0.004	0.09	0.004	0.02	0.004	0.019
20 MPH	0.03	0.004	-0.08	0.004	0.03	0.004	0.011
35 MPH	0.11	0.02	0.10	0.01	0.02	0.02	0.060
50 MPH	0.07	0.03	0.05	0.05	0.18	0.07	0.050

of these data points, FEAT obtained between 14 and 30 measurements. An oxygen reading of 5% was assumed for the first ETC reading for which oxygen was not noted; this was the value observed the other two times that the vehicle was in the same operating mode.

Table III shows an analysis of all of the FEAT intercomparison measurements taken on November 15, 1989 during the recorded time intervals. The time spans were noted in order to check that the vehicle emissions remained somewhat constant during the data-gathering process (i.e., writing down the ETC measurement values, coming outdoors, then writing down the FEAT measurement values).

Of 116 measurements, there was only one in which the computer declared the data points to be too deviant to calculate a %CO, indicating that the new interface solved the problems experienced with the rotofeat used on the first test day. The maximum standard deviation encountered in the data set was less than $\pm 1\%$ CO; the average standard deviation was 0.3% CO. This is a conservative measure of the precision of the FEAT instrument, since the vehicle variability is also included in the statistics. The number of points in each time period range from 14 to 30, a time span of 28 to 50 seconds. When measuring a calibration gas cylinder, 22 consecutive readings were obtained with an average of 9.63% CO and a standard deviation of 0.27% CO.

For the cold start 505 comparison, the original ETC data graph is shown in Figure 8, and the digitized ETC data are shown overlaid on the FEAT data trace in Figure 9.

Of the 242 FEAT beam breaks, there were 235 successful %CO measurements, and seven aborted measurements which the computer rejected for too much error in the CO/CO_2 slope. There were no error codes indicating an inadequate CO or CO_2 plume for detection. The FEAT unit determined the CO/CO_2 ratios corresponding to 14 to 16% CO for the first 70 seconds of the test. Note that ETC reported lower levels of CO (6 to 11%) in the first 40 seconds accompanied by very low levels of CO_2 (only up to about 2%). The oxygen data are not available on the ETC database in this mode, but it is apparent that the combustion system of this vehicle was operating poorly during the first minute of the test. For the first 30.3 seconds, the vehicle could not deliver the power to the dynamometer (set for 3000 lbs and 11.4 hp) required by the cycle protocol. If the dilution correction could have been applied, the ETC values would be higher during the first part of the test.

Conclusions

From Table II, it can be seen that FEAT and ETC agree on low CO-emitting

Table III: Statistical analysis of the 335 FEAT %CO readings for the blind (b) and open (o) intercomparison on 11/15/89.

Table III				
Total N (blind/open)	ETC %CO, dilution adjusted	Average FEAT %CO	Range Feat %CO	Standard Deviation %CO
30 (b)	8.01	7.7	8.65 - 6.65	0.35
30 (b)	3.16	3.12	2.86 - 3.42	0.61
23 (b)	3.45	3.18	2.87 - 3.36	0.16
19 (b)	7.47	7.02	6.75 - 7.47	0.19
14 (b)	3.16	3.01	2.79 - 3.27	0.15
41 (o)	7.85	7.20	6.55 - 7.70	0.26
22 (o)	8.01	7.51	7.05 - 8.02	0.30
37 (o)	8.27	7.70	7.00 - 8.27	0.31
44 (o)	3.79	3.70	3.27 - 4.53	0.27
40 (o)	3.36	3.41	2.73 - 3.92	0.24
35 (o)	2.28	2.30	2.06 - 2.65	0.14
Total: 335			Average Standard Deviation:	0.3% CO

vehicles to within error limits of less than ± 0.2% CO for individual FEAT readings. From Figure 7, it is apparent that there is excellent agreement even with the raw data. The five percent upwards correction based on the on-site calibrations, which would normally be carried out before FEAT data are reported, would put the points even closer to the 1:1 line. For the purposes of this intercomparison, it is appropriate to report the raw data for both calibrations and readings in order that any interested reader can perform the corrections independently. Accuracy and precision data are summarized in Table IV.

The general level of agreement between FEAT and ETC in the cold-start FTP

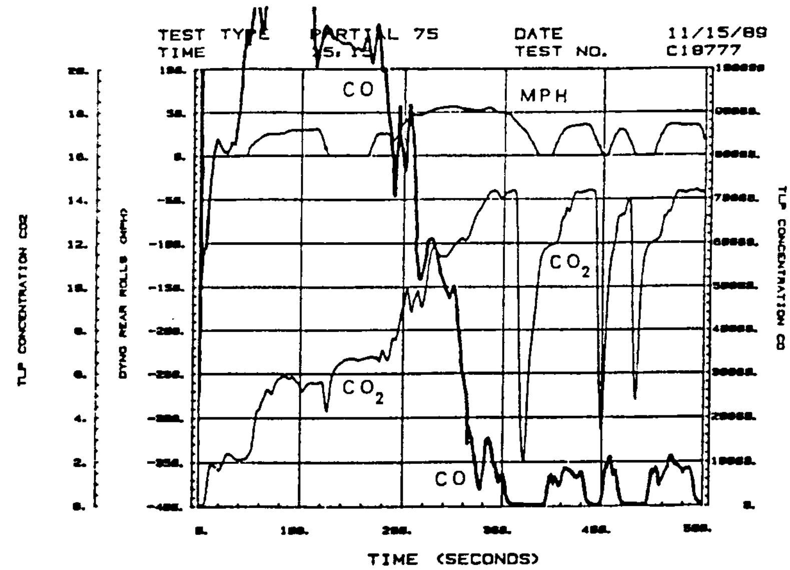

Figure 8 The ETC printout, with the CO trace emphasized. These data do not include any dilution adjustments, which always increases the CO and CO_2 values. These adjustments would be large for the first 70 seconds.

shown in Figure 9 is remarkable, particularly during the catalyst lightoff period between about 180 and 300 seconds, as well as the three small CO fluctuations during the last 200 seconds. There are apparently large pulses of air in the system which give rise to the

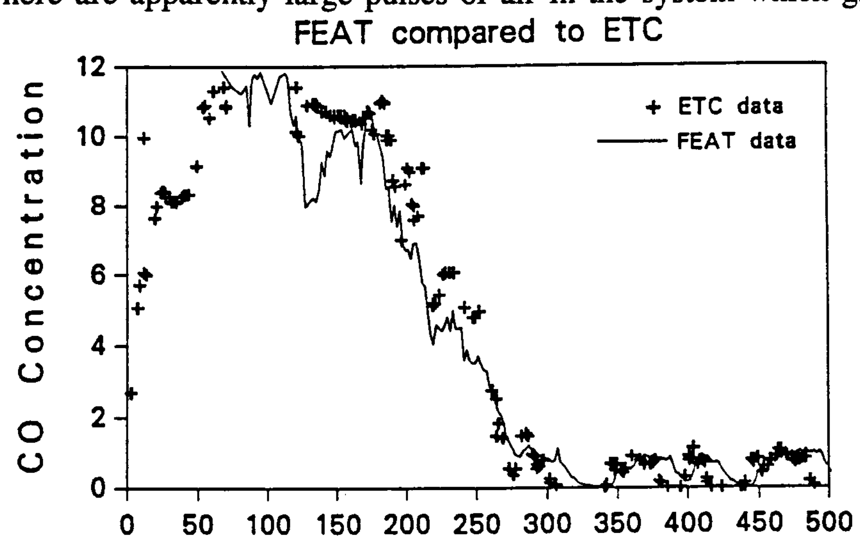

Figure 9 A time plot of FEAT (line) and dynamometer (points) when the ccold-start vehicle was undergoing a cold transient 505 cycle.

deep CO_2 dips corresponding to each time the vehicle drops rapidly into the idle mode. These pulses would cause large (and in this data set, unknown) fluctuations in the ETC

CO data; a dilution adjustment would be required for compatibility with simultaneous FEAT measurements. However, since the fluctuations occur when the ETC CO reads essentially zero (as does the FEAT), the lack of the oxygen dilution parameters is not important.

Table IV: Summary of FEAT measurement accuracy and precision.

TABLE IV	
Range	0 to 16%
Precision and Standard deviation	± 0.2% CO at 0% CO ± 0.3% CO at 10% CO
Accuracy depends on calibration cylinders, even with 2% certified gases, 5% errors are possible.	

Closer inspection of the data reveals that the long lines necessary to bring the exhaust from the dynamometer to the FEAT unit are causing a lag and a time response longer than the two second data acquisition rate determined by the frequency of the light chopper. The response lag is most noticeable when looking at the rapid time structure on the ETC trace around second 280, and at the long flat zero CO readings between 300 and 440. In every case, the FEAT readings do not go down as fast as the ETC readings.

A printout of the modal averages of the different modes of the cycle was supplied by ETC (See Appendix E). It is not possible to provide fully overlapping FEAT data for three reasons. The first, mentioned earlier, is that at the beginning of the cycle when the ETC CO_2 is very low, the oxygen concentrations must have been quite high (HC readings were close to 10% of the CO readings). The second is the problem of time lag. The third is that some of the modes are short and are odd numbers of seconds in length. Since the FEAT only reads every two seconds, some five second modes had to be treated as six, while adjacent 13 second modes were treated as twelve. These difficulties also precluded a regression analysis of FEAT data versus ETC data for this test.

With these caveats, Figure 10 shows the comparison of the 18 modes for which both instruments were operating (FEAT was turned on 16 seconds into the run). The effect of the lag is apparent since FEAT reads all decelerations as larger than ETC while on the accelerations from mode 9 onwards ETC shows a slightly higher reading. Even

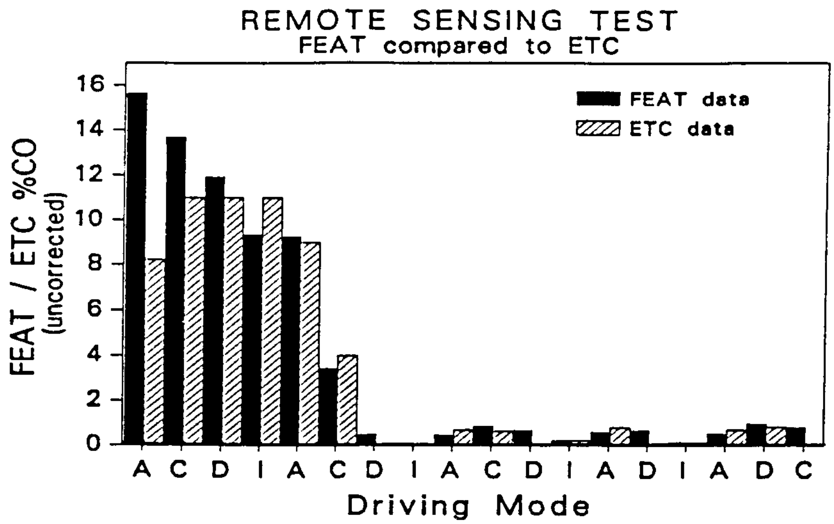

Figure 10 Modal average %CO from the last 18 modes of the cold transient 505 data shown in Figure 9. The letters indicate whether the mode is Accel., Cruise, Decel., or Idle. ETC data in this case are not dilution adjusted.

with the problems discussed earlier, only three modal averages show differences greater than 1% CO, and those are all in the very gross-polluting early time region at greater than 8% CO. The first mode and some of the second are in the first 70 seconds during which significant dilution adjustments are expected to be necessary.

VII. SUMMARY OF FINDINGS

The FEAT monitor is capable of making accurate, snapshot CO emission measurements of a fleet of on-road vehicles in real time (i.e., less than 1 second per measurement). This conclusion is supported by the findings of this project, which are detailed below.

o The theory behind the FEAT instrument, specifically, the equations for converting raw FEAT data to percent emissions, is sound and is not unique to FEAT. That is, data from conventional analyzers can be evaluated by the FEAT equations without appreciable error.

o The FEAT equations are valid throughout the useful range of automobile %CO emissions, and they do not appear to produce errors for vehicles with intermittently operating catalysts. A simultaneous reading using the FEAT device and its equations will agree with direct measurements of CO and CO_2; however, the snapshot nature of the FEAT measurement must be evaluated in the context of the operating mode of the vehicle since emissions can be variable in some modes.

o A number of useful quantities can be derived from the fundamental FEAT measurement of the CO/CO_2 ratio (called Q). These include tailpipe emissions as dry, undiluted exhaust %CO, mass emissions as gm CO/gallon of fuel burned, and units of combustion efficiency such as effective air-to-fuel ratio.

o Errors introduced by uncertainties in fuel composition and exhaust hydrocarbon emissions are small; furthermore, these small errors can be corrected by incorporating new information and/or instrumentation into the FEAT system.

o Accuracy and precision of the FEAT is comparable to instruments used for standard I/M idle tests. At low %CO, a conservative estimate of the precision is $\pm$ 0.2% CO, while at high %CO, precision is $\pm$ 0.3% CO. Typical accuracy is about $\pm$ 5% of the scale reading.

o Side-by-side measurements of exhaust %CO by the FEAT and a conventional laboratory monitor show excellent agreement. Regression of corrected FEAT %CO versus %CO as measured by the conventional monitor give a slope of 0.99, with a correlation coefficient of 0.99.

o The FEAT is capable of accurately monitoring rapidly changing CO emissions, such as encountered in a vehicle with an intermittently operating emissions system (e.g., a vehicle operated from a cold start). In its typical operation mode, however, the device obtains only one instantaneous measurement per vehicle.

VIII. FUTURE WORK

Because remote sensing approaches the problem of emissions control in a different manner than conventional methods, there is more to consider than merely whether remote sensing correlates well with a laboratory emissions procedure. The FEAT instrument is not designed to replace conventional procedures, but to add a new dimension to the field of emissions control. Therefore, evaluation of the instrument must of necessity include some discussion of its possible uses, as well as of parameters not testable under laboratory conditions.

Representativeness of a FEAT measurement

Although they have been shown to correlate well with conventional laboratory measurements, there are at least two additional concerns with regard to interpreting

FEAT measurements. First, the prototype FEAT instrument is the only one in existence. Therefore, it has not been possible at this point to determine the reproducibility or field precision between two FEAT instruments measuring the same sample. A second instrument should be built so that instrument variability can be evaluated. Such investigations are planned as part of a future EPA cooperative study.

A second source of potential variabiltity in a FEAT measurement concerns vehicle operating cycles. For instance, it is well-known that a vehicle's emissions may vary considerably depending on the operating conditions (i.e., cold engine, warm engine, under acceleration, at constant speed, at idle, etc.). Furthermore, vehicle operating mode will be influenced considerably by road conditions (by hills, stop signs, etc.). Any such effects must be characterized to determine if a snapshot measurement is biased relative to average emissions. It is also possible to conceive of conditions whereby no bias is introduced, but variability of a single measurement is increased. Therefore, investigations should be conducted regarding which vehicle operating mode is the most diagnostic for a particular application. The results of such a study could be used to identify sampling sites for the FEAT such that most vehicles passing those sites would be in the desired operation mode.

Potential applications

Two major application areas include gross emitter detection and fleet monitoring. Regarding the former, previous studies (3,4) have suggested that a substantial amount of urban pollution due to automobiles has its origin in relatively few vehicles. For various reasons (e.g., operating mode at the time of testing, or tampering with the emissions system), such vehicles may escape detection by conventional I/M emissions tests. In a study performed in Los Angeles (5), the FEAT was shown capable of identifying high emitters that had managed to pass the biennial California smog test (FEAT measurements were confirmed by roadside emissions testing). Given these results and those in this study, once research has determined suitable emissions standards and appropriate field siting criteria, FEAT should be able to efficiently discriminate between high and low emitters. In this application, FEAT could be used to either supplement or replace conventional I/M testing. Another possibility is to use the FEAT to identify high-emitting vehicles whose drivers would be notified and allowed to act voluntarily to correct their vehicles' emissions problems.

Fleet monitoring

In theory, the ability to determine emissions for large numbers of vehicles in a short period of time uniquely qualifies the FEAT for on-road evaluation of fleets of vehicles. Since the standard error is inversely proportional to the square root of the number of measurements made, the mean emissions value for a large fleet of cars can be known with high precision. This fact would allow statistically significant comparisons to be made between two different fleets of vehicles. For instance, the effectiveness of an I/M program could be evaluated by obtaining mean fleet %CO emission values for vehicles from both inside and outside the emissions-controlled area and determining to what extent the means are statistically different. Similarly, data could be stratified according to model year, make, registration jurisdiction, etc. Previous studies have indicated some interesting preliminary results (3,4,5,6).

Because the FEAT system can obtain registration information for vehicles as well as emissions data, information could be compiled for specific models. A particularly interesting potential application would be to monitor new vehicle models for systematic high emission rates. If a new model of automobile were to show abnormally high emissions compared to other vehicles of the same model year, this could be an indication of vehicle malfunction. The automobile manufacturer could be notified and could take steps to correct the problem, including a recall, if necessary. The ability to determine a malfunction early could afford advantages in emissions reduction compared to current methods.

Because FEAT measurements are easily converted to gm CO/gallon of fuel, there exists the potential to use the FEAT for regional CO emissions modeling. A major advantage of gmCO/gallon readings over the conventional gm/mile units is that they depend only on the engine and emission system operating characteristics. Gram per mile emissions also depend on the vehicle transmission setting and speed; in fact, gm/mile has an infinite singularity at zero speed. If FEAT measurements are carried out at several locations in a non-compliance region, then the average gm/gallon can be multiplied by gallons sold (available from the state revenue department). Such an approach would allow remote sensing to contribute to a regional mobile source inventory without the need to carry out extensive Vehicle Mile Travelled (VMT) surveys. If gridded data are required, the fuel combustion data would need to be proportioned into this format (i.e., analogous to the gridded time or VMT of the current methods); however, the total would be constrained by the sales statistics.

It should be noted that the realization of these applications will require further research to identify the important variables and to implement protocols that will ensure accurate characterization of fleet emissions.

<u>Research required</u>

Some potential applications of the FEAT are apparent; with the present state of knowledge about the capabilities of the FEAT, relatively little effort would be required to implement testing programs. Other potential applications, however, are more speculative at this time and further research will be required to determine if they are feasible. A number of these investigations are either underway or in the planning stages.

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APPENDIX A

DETAILED CALCULATIONS

In this appendix, quantities such as dry, undiluted exhaust %CO, air-to-fuel ratio, and gms CO/gallon of fuel burned are derived from the remotely-measured value of Q. For this purpose, dry air is assumed to have the formula $0.21O_2 + 0.79N_2$. It is interesting to note that (0.21 x 2) = 0.42 and 0.79 appear throughout the final equations, sometimes with added integers (such as 2.79). Reappearance of these numbers is one advantage of carrying out all calculations in molar rather than mass units.

All of the derivations are based on a standard combustion equation. If HC and NO_x emissions (and H_2 from the water gas reaction; see below) can be considered small compared to the CO, CO_2, and N_2 concentrations emanating from the tailpipe, this equation takes the form:

$$CH_n + m(0.21O_2 + 0.79N_2) \rightarrow \frac{n}{2}H_2O + aCO + bCO_2 + 0.79mN_2 \qquad [1]$$

Because under all circumstances the large majority of the exhaust is N_2 and CO_2, these assumptions introduce either essentially no error (e.g., in the determination of exhaust %CO and $\%CO_2$) or a small, readily correctable error (e.g., in the determination of gm CO/gallon of fuel burned and air-to-fuel ratio) into the quantities derived from remotely-sensed Q.

From eq. 1, the following relationships are obtained:

$a + b = 1$ (by carbon balance),

$0.42m = n/2 + a + 2b$ (by oxygen balance),

and $Q = a/b$ (by remote sensing).

When a and b are determined in terms of Q, one obtains:

$$a = Q/(1 + Q)$$

and

$$b = 1/(1 + Q).$$

Thus, with a knowledge of n and Q, the molar coefficients in the balanced combustion equation are readily determined; these quantities are in turn used to obtain other derived quantities.

Derivation of the exhaust mole %CO and %CO_2

If CH_2 is used for the empirical formula of the fuel, then n in eq. 1 is 2, and furthermore,

$$m = (1 + a + 2b)/0.42.$$

One then obtains:

$$dry\ CO_2\ fraction = \frac{b}{1 + 0.79m} \qquad [2]$$

Note that any percentage errors in m caused by the assumption of n = 2 will be halved for most vehicles, since n is divided by 2 in this derivation. Upon substitution for b and m, one obtains:

$$\text{fraction of } CO_2 = (1/(1+Q))/(1+0.79(3+2Q)/0.42(1+Q)).$$

After multiplying throughout by 0.42(1+Q),

$$\text{fraction of } CO_2 = 0.42/(0.42+0.42Q+2.37+1.58Q)$$

$$= 0.42/(2.79+2Q),$$

from which is obtained:

$$dry\ \%CO_2 = \frac{42}{2.79+2Q} \qquad [3]$$

Similarly,

$$dry\ \%CO = \frac{42Q}{2.79+2Q} \qquad [4]$$

It is often convenient to express the equations in the forms:

$$dry\ \%CO_2 = \frac{100}{6.64 + 4.76Q} \qquad [5]$$

and

$$dry\ \%CO = \frac{100Q}{6.64 + 4.76Q} \qquad [6]$$

The values obtained from these equations assume dried and undiluted exhaust. If these values are to be compared to conventional tailpipe measurements in which excess air is present, the tailpipe %CO values need to be adjusted upwards by a dilution factor of 21/(21 - %O_2).

Determination of effective A/F ratio

The molar air to fuel ratio (A/F), is given by:

$$Molar\ A/F = m = \frac{\frac{n}{2} + a + 2b}{0.42} = \frac{\frac{n}{2} + \frac{1}{1+Q} + 1}{0.42} = \frac{2 + \frac{n}{2} + Q\left[1 + \frac{n}{2}\right]}{0.42(1+Q)}$$

For fuel of empirical formula CH_2, n = 2 and

$$A/F = \frac{3 + 2Q}{0.42(1 + Q)} \qquad [7]$$

If the fuel has a different C:H ratio, then this calculation will be in error. However, for small values of Q (most vehicles) an 8% error in the assumed C:H ratio results in only a 4% error in calculated A/F ratio.

The A/F ratio used by mechanical engineers is by weight. To obtain the engineering units, the molar ratio should be multiplied by 29/(formula weight of the empirical fuel unit; i.e. as CH_n). For example, in the case of n = 2, multiply by 29/14.

Note that unburned HC or evaporative emissions will increase the actual fuel use, and an air pump or excess combustion air would increase the actual air throughput. This calculation only refers to air participating in combustion either in the engine, catalyst, or exhaust system.

Determination of gm/gallon CO emissions

The ratio of CO to CO + CO_2 is a measure of CO emissions in moles of CO per mole of carbon in the fuel (assuming HC emissions to be negligible in comparison), thus:

$$CO/(CO + CO_2) = a/(a + b) = a.$$

From equation 1,

$$a = Q/(1 + Q).$$

For conversion of moles of CO to grams of CO, this term is multiplied by the formula weight of CO, 28 gm/mole. For conversion of moles of carbon in the fuel to gallons of fuel, the approximate fuel formula $CH_{1.85}$ (13.85 gm/mole) is assumed. The density of gasoline is about 700gm/liter, and there are 3.78 liters per gallon. Incorporation of these conversions yields the equation:

$$CO\ gm/gallon = \frac{3.78 \times 28 \times 700Q}{13.85(1+Q)} = \frac{5300Q}{1+Q} \qquad [8]$$

Note that this equation is approximate and neglects any contribution from exhaust HC.

The FEAT gm/gallon equation can also be derived from the Federal EPA miles/gallon equation (Eq. 9). The EPA MPG calculation is based upon exactly the same combustion equations used in the FEAT system. The numbers look more complex since mass units are used instead of molar units. The EPA MPG equation reads:

$$MPG = \frac{2421}{0.866HC + 0.429CO + 0.273CO_2} \qquad [9]$$

where HC, CO and CO_2 are expressed in gm/mile and HC is assumed to be $CH_{1.85}$. Since gm/gallon equals gm/mile multiplied by miles/gallon,

$$0.429\,CO(gm/gal) = 2421 - 0.273\,CO_2(gm/gal) - 0.866\,HC(gm/gal) \qquad \textbf{[10]}$$

The FEAT system measures Q = CO/CO_2 in molar units. The conversion to mass units is given by:

CO/CO_2 in mass units = Q*28/44.

Future versions of the FEAT system will measure Q' = CO/HC, where Q' is also a molar ratio. Conversion to mass units is achieved by:

CO/HC in mass units = Q'*28/13.85.

Substituting into equation 10, we obtain:

$$0.429\,CO = 2421 - 0.273\frac{44\,CO}{28Q} - 0.866\frac{13.85\,CO}{28Q'}$$

$$12Q\,CO = 67{,}800Q - 12\,CO - \frac{12Q\,CO}{Q'}$$

$$12\,CO\frac{1+Q+Q'}{Q'} = \frac{5650Q}{1+Q+\frac{Q}{Q'}}$$

$$CO\ gm/gallon = \frac{5650Q}{1+Q+\frac{Q}{Q'}} \qquad \textbf{[11]}$$

As shown above, a simplified equation was derived neglecting HC and dropping one significant figure. This equation was:

$$CO\ gm/gallon = \frac{5300Q}{1+Q} \qquad [8]$$

A typical fleet average for Q is 0.1; using this value, the results of this simplified equation and the hydrocarbon-corrected equation are essentially identical. Since the FEAT does not currently measure HC, use is made of FTP data, which shows that the ratio of CO to HC emissions is about 12.5 (in molar units) to a high degree of correlation (2). This allows for an approximate correction for HC, i.e.,

$$CO\ gm/gallon = \frac{5650Q}{1+1.08Q} \qquad [12]$$

If the CO/HC ratio were actually 10, the equation reads:

$$CO\ gm/gallon = \frac{5650Q}{1+1.1Q} \qquad [13]$$

For a gross-polluting vehicle (e.g., Q = 1), the HC addition increases the gm/gallon by only 6% from the simple formula in which HC is not included at all. These calculations demonstrate that lack of measurement of HC has little effect on the CO equations; neglecting HC entirely leads to errors less than 6% for 95% of vehicles, and a parameterized HC correction reduces the error further.

Since the next generation of FEAT systems will be able to measure Q', accurate tailpipe gm HC/gallon estimates will become available in addition to slightly more accurate gmCO/gallon estimates.

It is important to note that all these per-gallon calculations refer only to fuel which exits via the tailpipe; vehicles with large evaporative or other fuel losses will use more gallons than these tailpipe-based equations assume.

Effect of the Water Gas Shift Reaction

There is a reaction known as the water gas shift reaction in which the exhaust CO reacts (sometimes on the catalyst) with exhaust H_2O to form CO_2 and hydrogen (H_2).

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad K \simeq 3.5 \qquad [14]$$

To illustrate the effect of this equilibrium, consider a vehicle burning CH_2 fuel which is producing exhaust with a Q value of 1 (i.e., 8.8% CO) in the absence of the water gas shift reaction. The composition of such exhaust (again, neglecting NO_x and HC) would be:

$$H_2O + 0.5CO + 0.5CO_2 + 5.95*0.79N_2.$$

Using the value of K given in Eq. 14, one can calculate the maximum extent to which the water gas shift reaction can occur; this corresponds to 30% of the CO reacting according to Eq. 14. The composition of exhaust undergoing this reaction to completion would be:

$$0.86H_2O + 0.36CO + 0.14H_2 + 0.64CO_2 + 4.7N_2$$

The remote sensor would correctly find Q = 0.36/0.64 = 0.562, and calculate exhaust %CO as:

$$42*Q/(2.79 + 2Q) = 6.03\%.$$

$$\textit{In fact, dry exhaust } \%CO = \frac{0.36 \times 100}{0.36 + 0.14 + 0.64 + 4.7} = 6.16\%.$$

Thus, for a very "dirty" vehicle, the water gas shift reaction can be shown to cause only a small error in reported %CO. For the majority of clean vehicles, %CO is small and the effect is even smaller.

Table A-1 brings together in summary form the relevant equations for emissions as a function of Q for three extreme vehicle fuels (carbon, CH_2 and CH_4). The equations and derivations are independent of the nature of the vehicle or of its emissions system. The equations are slightly dependent on the chemical nature of the fuel, but the dependence is small because the largest fraction of the exhaust, namely nitrogen, is constant.

It is interesting that for these three simple cases, most of the coefficients are integers or integers plus 0.42 (twice the 0.21 fraction of oxygen, O_2, in air). These parameters are derived from the remotely measured values of Q; the determination of Q would be carried out correctly independent of the fuel chemistry.

The EPA fuel economy equations are based on the same combustion equations as are used in all the derivations above. As discussed in the Federal Register, there are no corrections required for differences in the vehicle or for the presence, absence, or type of emission system. There are small corrections required for the density and the carbon-to-hydrogen ratio of the fuel. For normal gasolines, the density differences are not large. One can also readily calculate from the derived formulas above that the corrections arising from a lack of knowledge of fuel carbon-to-hydrogen ratio are not large.

Table A-1: Solutions for C, CH_2, and CH_4

Fuel	*Formula*	*A/F in moles*	*Exhaust CO Fraction*
Carbon	C	$\frac{2+Q}{0.42(1+Q)}$	$\frac{2-0.42A/F}{1+0.79A/F} = \frac{0.42Q}{2+1.21Q}$
Gasoline	CH_2	$\frac{3+2Q}{0.42(1+Q)}$	$\frac{2-0.42A/F}{1+0.79A/F} = \frac{0.42Q}{2.79+2Q}$
Natural Gas	CH_4	$\frac{4+3Q}{0.42(1+Q)}$	$\frac{4-0.42A/F}{1+0.79A/F} = \frac{0.42Q}{3.58+2.79Q}$

It is instructive to calculate the errors in %CO that arise for extreme cases of fuel carbon-to-hydrogen ratio when a fuel of empirical formula CH_2 is assumed. For instance, a vehicle which has enough air to burn all its fuel carbon to CO_2 (i.e., Q = 0) always has an exhaust %CO of zero, independent of C/H ratio (i.e., zero error). The errors increase with increasing Q, but remain surprisingly small. For a vehicle in which a CO/CO_2 ratio of one is observed (i.e., a high emitter), the %CO will be reported as 8.8 if the FEAT is assuming a fuel composition of CH_2; if the vehicle were actually running on pure carbon (C/H of 1:0) the actual value would be 12.0, a -27% error. Going to the other extreme, if the vehicle were powered by CNG (methane, CH_4) with the maximum possible C/H ratio of 1:4 for a hydrocarbon fuel, the correct value would be 6.6; i.e., a +33% error. Errors introduced by drastic changes in fuel oxygenation are not large mainly because the major exhaust percentage is always nitrogen. These errors are also completely correctable if the fuel C/H ratio is known.

The combustion equations for 2% and 4% fuel oxygenation are also readily solved. The resultant equations show that the remote sensor would underreport by a percentage equal to half the oxygenation percentage. These small corrections can be taken into account where the degree of oxygenation is known; e.g., in previously published work (8).

The conversion from %CO to gm/gallon can be calculated from the equations given earlier. The simplest equation neglecting HC is:

$$gm/gallon = \frac{5300 \times 2.79 \times \%CO}{42 - 0.79 \times \%CO} \qquad [15]$$

Because the denominator has the value 42 - 0.79*%CO, and %CO is usually « 10, the nonlinearity in converting %CO to gm/gallon is rather small. Table A-2 shows solutions of the above equations for some characteristic %CO readings converted to grams of CO per gallon of fuel.

Table A-2 Percent CO converted to grams CO/gallon of fuel and grams CO/mile for a 20 MPG vehicle

Percent CO	grams CO/ gallon	grams CO/ mile
0.0	0	0
0.5	178	9
1.0	360	18
1.5	544	27
2.0	732	37
3.0	1121	56
4.0	1525	76
5.0	1945	97

APPENDIX B

ETC LABORATORY INFORMATION

MILTON ROY
Environmental
Division

1859 Jasper Street
Aurora, Colorado 80011
(303) 344-5470

LABORATORY INFORMATION

Environmental Testing Corporation occupies a twenty thousand square foot test facility just 15 minutes from Denver airport. The three test cell facility has been in operation since 1979 and has provided most major manufacturers of automobiles with reliable vehicle emissions testing services. E.T.C. has multiple test sophistication levels from 'bag' analysis to catalyst efficiency testing. Additionally, data presentation is available on the basis of chart recordings to computer printout and graphics.

Modifications to the data acquisition and control system are in progress in order to increase the capabilities of the test facility and to further improve system reliablity.

In addition to standard test proceedures, E.T.C. has the capability of performing evaporative emissions at various temperatures and durations. Modification are currently being made to the third test cell to perform cold emissions testing at the proposed 20 degree level. The cold cell is expected to be in operation in February 1990.

The staff has a combined total experience in vehicle emissions testing in excess of 60 years.

FACILITY DESCRIPTION

- 20,000 square foot building
- Three temperature and humidity controlled test areas
- Temperature controlled soak area
- A separate instrument room with controlled temperature and humidity for analytical equipment, computer, and particulate filter weighing and conditioning
- Separate area for vehicle entry, washing, and fueling
- Adequate shop area with vehicle lift and work area
- Adequate customer office area

EQUIPMENT DESCRIPTION

- Clayton ECE-50 dynamometers with Road Load Power Control and Direct Drive Inertia ranging form 1000 to 8875 pounds in 125 pound increments
- Combination Bag analysis/Dilute modal analysis consoles for gasoline or diesel light duty vehicles
- Catalyst efficiency consoles with dual sample streams
- Video drivers aids
- CFV-CVS with nominal flow rates of 325 to 600 CFM
- Dilution tunnel and associated particulate equipment
- Exhaust emission data acquisition and control systems with printers and plotters
- Sealed Housings for Evaporative Determination
- S.H.E.D. consoles with Hydrocarbon analysers and data acquisition and control systems
- Fuel conditioning equipment
- Dew point hygrometers
- Compensated aneroid barometer

TEST CAPABILITIES

The E.T.C. vehicle emissions test system provides the overall control and data handling for a chassis dynamometer emissions test. The system includes:

Automated analyzer bench control and data analysis including:

- Pre-test zero/span and range control checks
- Automatic zero and span compensation
- Automatic input of ambient conditions fron transducers
- Modal test data analysis and computation
- Automatic analyzer range control, bag reading, and analysis including switching between high and low instruments
- Drivers trace presentation
- CFV control and data input
- On-site test data reporting
- Custom shift point schedules
- Custom test trace schedules
- Coast down checks

The following test configurations are available:

- Bag analysis only test
- Dilute modal plus bag analysis test
- Raw tailpipe plus bag analysis test
- Converter efficiency plus bag analysis test
- Developement options for detailed analysis including:
  - Second by second data storage
  - Storage of temperatures, pressures, and other parameters
  - Modal fuel economy calculations
  - Modal air/fuel calculations

Environmental Testing Corporation offers both the equipment and the staff to perform vehicle emissions tests for certification and developmental purposes. If these services are desired by your comapny, contact E.T.C. at (303) 344 5470 or by fax at (303) 361 6174.

Al Papay President

MILTON ROY
Environmental
Division

1859 Jasper Street
Aurora, Colorado 80011
(303) 344-5470

PRICE SHEET EFFECTIVE JANUARY 1, 1988

TEST TYPE:	'78 CVS	HWFET	HOT 505	'74 CVS
Base Price/Bag Analysis	750	350	300	500
ADDITIONAL ANALYSIS:				
Modal Analysis (with A/F Ratio)	150	70	70	105
Integrated HC (Required on Diesels)	80	50	50	60
Diesel Particulate	220	105	105	140
Catalyst Efficiency (with A/F Ratio)	375	185	150	240

OPTIONAL TESTS AND SERVICES:

Steady State following '78 CVS test	10/mode
Preconditioning Cycle	175
Drain & Refuel	70
Evaporative Emissions (Diurnal)	175
Evaporative Emissions (Hot Soak)	95
Simulated Diurnal	95
H.W.F.E.T. Warm-up Cycle	125
Dynamometer Time (No Analysis)	220/hr.
Graphics Presentation of Test (per graph)	25
Vehicle Coast-Down Check	140
Steady State only (note: minimum charge 1 hr.)	700/hr.
Pressure-check System	30
Install Device or Remove Device	50

NOTE: Prices for optional test cycles, special tests and exclusive shift use will be quoted upon request.

Certification Quality - Add 10%.

Prices for cold ambient testing and related procedures are 1.5 times the above prices.

Weekend work or overtime work is 1.5 times the above prices.

APPENDIX C

PROTOCOLS

PROTOCOLS

for

THE UNIVERSITY OF DENVER
Department of Chemistry
University Park
Denver, Colorado 80208-0179

DYNAMOMETER TESTS

ATTENTION: Marc Pitchford
U.S. Environmental Protection Agency
Environmental Monitoring Systems Laboratory
P. O. Box 93478
Las Vegas, Nevada 89193-3478

One of the tasks to be performed under the present contract is to compare vehicle exhaust %CO (dry and air corrected) as measured on a dynamometer, with vehicle exhaust as measured by the University of Denver CO remote sensing system (FEAT). Several suggestions on how to achieve these goals were provided in a memorandum from W. Clemmens to M. Pitchford on February, 2, 1989. The memorandum includes the following guidelines:

Goal...Accuracy and precision data for the identification of %CO and %CO_2 in the ranges 0-10% and 0-16% respectively.

Overview...Test up to four passenger cars on a chassis dynamometer at several steady state speeds and at multiple loads with no malfunctions, and with preinduced malfunctions to vary the tailpipe CO and CO_2 concentrations.

Suggested test vehicles were:

1... Toyota 4 cylinder with MPI; inducible malfunction bad catalyst.

2... GM - V6 with MPI or TBI; inducible malfunctions disconnect O2 sensor...aftermarket PROM

3... Ford or GM 302 V8 with MPI or TBI; inducible malfunctions; misfire? no downstream air; bad catalyst; aftermarket PROM.

4... Optional Nissan NAPS-Z or CA Engine with MPI

A matrix of speeds and loads was suggested namely

speed/load mph	9hp	15hp	30hp	50hp
15	x	x		
30	x	x	x	x
50			x	x

Three items of equipment are needed:

Emissions bench

Variable load dynamometer

Equipment to simulate field operation of the remote sensor

The suggested test procedure included running each test three times, with the EPA Project Officer (EPAPO) exercising some real time decision making in order to achieve the range of emissions required, and to attempt to achieve similar CO concentrations from different combinations of speed and load.

Suggested data analysis includes converting all the data to dry and air corrected units such as reported by the FEAT device; analysis of scatter plots of paired CO and CO_2 data in terms of linear, and best nonlinear, polynomial fit. The use of Air Force AEDC-TR-78-5 to determine bias error, precision error and measurement uncertainty is recommended.

Bearing in mind these suggestions, the following protocols are proposed.

TEST DATE: November 1, 1989, Wednesday

LOCATION: Environmental Testing Corporation (ETC)
1859 Jasper Street
Aurora, CO 80011
Phone: 344-5470

TIME: 8:30 A.M. - 5:00 P.M.

INVITATION LIST: Advisory Committee and any other interested parties

TEST VEHICLES

Vehicles available to the University of Denver.

1) Late model Toyota, 4 cyl. with MPI

2) 1977 Volkswagon, 2L, 4 cyl with MPI, but no catalyst (substitute for 1) with disabled catalyst)

3) General Motors V6 with MPI

4) Ford 302 V8 with MPI

INDUCIBLE MALFUNCTIONS

Vehicle 3) Disconnected O_2 sensor.

The owner of vehicle 4) has not yet been asked for permission to disconnect one spark plug.

Vehicle 2) can be adjusted up to 10% CO in its exhaust by means of manual adjustment to the intake air sensor.

SPEED/LOAD MATRIX

Mr. A Papay of ETC suggested that each vehicle should first undergo steady state testing at the load specified for that vehicle and engine class in the EPA guidelines for the FTP. He also suggested doubling that load for the second set of tests. In this way the initial set of steady state runs will be comparable to the steady state periods of the FTP cycle. The higher loads which will be provided in the second set of tests will then also be matched to the vehicle's expected level of performance.

Loads to be run in Steady-State-Mode:

1. FTP load for that vehicle

2. Double FTP load for that vehicle

Speeds: 10, 15, 30, 50 mph.

All speeds and loads to be run on all vehicles

EQUIPMENT AVAILABLE:

Environmental Testing Corporation is certified by the EPA as an emissions testing laboratory. Information on the ETC quality assurance and quality control audits is available from A. Papay at the above address. ETC has available two 50 hp variable load Clayton dynamometers with full CVS and exhaust gas analytical procedures. The data are collected on an HP2100 computer system. As discussed earlier, equipment required for this test includes dynamometer, analytical equipment, and an interface to persuade the FEAT system that it is looking at passing vehicles when in fact it is looking at a steady state emission.

ETC will provide the first two equipment items, namely the "South" dynamometer with full raw exhaust gas analytical capability for CO, CO_2, HC, and O_2. These items of equipment are certified standard equipment and are fully described elsewhere. Exhaust from the south dynamometer is diluted in the CVS equipment and passes out through the wall into the parking lot.

University of Denver Carbon Monoxide Remote Sensor (FEAT) complete with calibration cylinders will be located in the adjacent parking lot. It is appropriate to note here that a comparison of FEAT measurements to those from a vehicle of instantaneous known (and operator controlled) emissions has been carried out in a true on-road comparison. Such a vehicle was available in January of 1989 when Dr. S. Cadle of General Motors conducted a blind, drive through intercomparison. The 42 data points which formed the database were reported to GM without any knowledge of the vehicle status at the time of the measurement. The correlation study showed a slope of 1 and a correlation coefficient (R^2) of 0.95 (General Motors, Private Communication, August 1989).

The last piece of equipment required for this dynamometer intercomparison is the hardware necessary to simulate a passing vehicle in such a way that the University of Denver FEAT system can otherwise utilize the identical hardware and software used for on-road vehicle testing (see Figure 1).

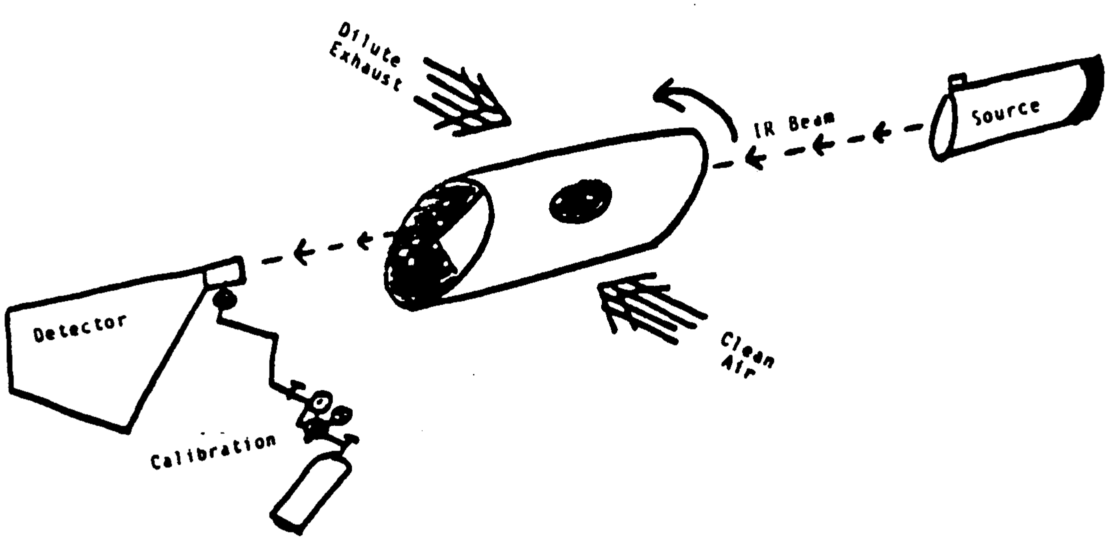

Figure 1. Schematic diagram of the ROTOFEAT apparatus which enables the FEAT System to monitor exhaust gas from a stationary vehicle using software and hardware identical to on-road conditions.

The ROTOFEAT apparatus has been developed and tested for this application. It consists of a hollow cylinder rotating approximately once every 1.6 seconds. The infrared beam from the FEAT unit is aimed so that it passes parallel to the axis of the drum close to its inside edge. A fixed opaque quadrant rotating with the drum provides 400ms of blocked beam on each rotation. This beam block simulates a vehicle wheel and triggers the program to a) remember the signals before beam blockage, and b) look for exhaust during the 500 ms after the intensity returns to normal. The 6" diameter hole in the cylinder rotates alternately so as to sample from two large flows of air. From the left, as illustrated, comes a fraction of the diluted exhaust from the CVS vent into the parking lot. From the right is pumped a stream of clean air. While the quadrant blocks the beam, the exhaust fills the tube. During the half-second after the beam returns to normal, the clean air supply dilutes the exhaust, ultimately returning the cylinder to a clean condition before the beam is blocked again by the quadrant. This dilution is essential, since the FEAT System looks for the time-dependent correlation of CO and CO_2 behind the vehicle compared to the readings for CO and CO_2 taken in front.

Calibration is performed by the same techniques as on the road (i.e., a short puff of calibration gas is added to the beam after the beam has been blocked, but with no vehicles around). In the case of the ROTOFEAT system, the exhaust flow in the general area is maintained, but the side hole in the tube is plugged, so that no exhaust enters the beam chamber.

GOAL

To exercise the comparison of dynamometer and FEAT exhaust gas measurements over as wide a range of operating parameters as is reasonably available.

PROTOCOLS

1) Calibrate FEAT and exhaust gas monitors, report results to the EPA project officer (EPAPO) who will be in charge of the intercomparison and will adjust any protocols as necessary in order to meet the goals.

2) Set vehicle on dyno, run at steady state 15 mph FTP load.

3) Re-calibrate FEAT with typical exhaust flow in the parking lot - report re-calibration to EPAPO.

4) ETC exhaust gas analyst reports to EPAPO that emissions are at steady state and reports dry exhaust percent CO, CO_2, O_2 (1). DU reports CO, CO_2 to EPAPO without knowledge of ETC data. ETC provides three more readings CO, CO_2, O_2. DU provides two more readings CO, CO_2. Vehicle speed altered to next speed/load and 4) repeated.

5) Change load -- repeat 4).

6) Change vehicle -- repeat 4) and 5).

7) Induce malfunctions and repeat as described earlier.

EPAPO has the option to ask for more data at a given load/speed, or otherwise alter protocols at his judgment during the experiment, in collaboration with the DU and ETC staff.

OPTION

If the EPAPO is satisfied that the preliminary goals have been met, then there is an option to attempt real-time intercomparison. One of the available vehicles, selected by the EPAPO will be placed on the dynamometer and run through a cycle, such as the FTP speed/time protocols. DU and ETC will do their best to synchronize clocks and share their data in order to obtain the best possible readings. Data intercomparison will be handled by the University of Denver with peak values being reported to the PM in real time to allow assessment of the progress of the experiment.

8) Return one vehicle to steady state condition.

9) Re-calibrate FEAT

10) Recalibrate ETC instrumentation

11) Report results of calibrations to EPAPO.

Within seven days, ETC and DU will report any necessary data corrections to the EPAPO. After this time, the EPAPO carries out preliminary analysis and releases the data to all participants. Up to this time, ETC and DU steady state data have been distributed blind to the EPAPO.

DATA ANALYSIS

With allowable malfunctions, replicate CO and CO_2 data for six vehicles, four speeds, two loads, will be available from the steady state studies. This will provide a minimum of 2x2x6x4x2 = 192 CO and CO_2 data points from which a statistically significant correlations can be derived. In fact, ETC collects data every four seconds and DU three data points in four seconds. Very large data sets can be constructed if this database is fully utilized. With the exception of the real-time cycle option discussed above, all data analysis will be carried out exactly according to the protocols suggested in the memorandum from W. Clemmens to M. Pitchford on February, 2, 1989.

APPENDIX D

DATA SUMMARY

The data contained in this appendix are raw, uncorrected data from November 1, 1989.

Vehicle #9650
1987 Toyota Tercel

Load	Speed	ETC %CO	FEAT* %CO	Comments
Road	10	0.004	*	Low exhaust levels
Road	10	0.004	*	
Road	10	0.004	*	
Road	20	0.004	*	
Road	20	0.004	*	
Road	20	0.004	*	
Road	35	0.004	0.05	
Road	35	0.005	-0.02	
Road	35	0.004	-0.08	
Road	50	0.004	0.04	
Road	50	0.004	-0.01	
Road	50	0.004	-0.04	
Triple	10	0.004	*	Low exhaust levels
Triple	10	0.004	*	
Triple	10	0.005	*	
Triple	20	0.004	*	
Triple	20	0.004	*	
Triple	20	0.004	*	
Triple	35	0.004	-0.05	
Triple	35	0.004	0.00	
Triple	35	0.004	-0.06	
Triple	50	0.14	0.08	
Triple	50	0.56	0.37	
Triple	50	0.16	0.04	

*Note that FEAT reads %CO from clean vehicles on either side of zero. An individual negative reading does not mean that the vehicle was cleaning the air. Negative numbers are left in the database in order to correctly indicate the system precision, and also in order not to upwardly bias the mean obtained from measured fleets.

Vehicle #7380
1988 Ford Thunderbird

Load	Speed	ETC %CO	FEAT %CO	Comments
Road	20	0.09	0.32	Vehicle was unable to be driven at 10 mph.
Road	20	0.03	0.18	
Road	20	0.02	0.17	
Road	35	0.01	0.05	
Road	35	0.01	-0.02	
Road	35	0.01	0.11	
Road	50	0.01	0.00	
Road	50	0.01	-0.05	
Road	50	0.01	-0.02	
Triple	10	0.003	-0.04	
Triple	10	0.003	-0.11	
Triple	10	0.004	0.06	
Triple	20	0.03	0.10	
Triple	20	0.02	0.06	
Triple	20	0.02	0.05	
Triple	20	0.02	0.03	
Triple	35	0.01	0.01	
Triple	35	0.01	0.04	
Triple	35	0.01	0.07	
Triple	35	0.01	0.05	
Triple	50	0.02	0.08	
Triple	50	0.02	0.00	
Triple	50	0.01	0.00	
Triple	50	0.01	0.02	

Vehicle #2314
1986 Oldsmobile Cutlass

Load	Speed	ETC %CO	FEAT %CO	Comments
Road	10	0.005	-0.02	
Road	10	0.005	-0.02	
Road	10	0.005	0.06	
Road	20	0.005	0.08	
Road	20	0.005	-0.03	
Road	20	0.005	-0.03	
Road	35	0.02	0.07	
Road	35	0.01	-0.04	
Road	35	0.005	0.01	
Road	50	0.008	-0.02	
Road	50	0.006	-0.04	
Road	50	0.03	-0.02	
Triple	10	0.004	-0.04	
Triple	10	0.004	0.09	
Triple	10	0.004	0.02	
Triple	20	0.004	0.03	
Triple	20	0.004	-0.08	
Triple	20	0.004	0.03	
Triple	35	0.02	0.11	
Triple	35	0.01	0.10	
Triple	35	0.02	0.02	
Triple	50	0.03	0.07	
Triple	50	0.05	0.05	
Triple	50	0.07	0.18	

Vehicle #4279
1977 Volkswagen Van

Load	Speed	ETC %CO	FEAT %CO	Comments
Road	10	1.82	1.92	
Road	10	1.77	1.88	
Road	10	1.74	2.04	
Road	20	1.90	1.71	
Road	20	1.81	1.78	
Road	20	1.86	2.44	
Road	35	1.69	1.62	
Road	35	1.72	1.55	
Road	35	1.80	1.56	
Road	50	2.44	1.67	
Road	50	2.50	1.62	
Road	50	2.45	1.78	

APPENDIX E

DATA SHEETS

01 ENVIRONMENTAL TESTING CORPORATION
STEADY STATE
01 NOV 89 14:55

TEST RUN NUMBER C18712
PRE - TEST

SPEED	:0	TEST NUMBER	:C18712
BARO (MMHG)	:632.5	WET BULB (DEG. F)	:52.42
DRY BULB (DEG.F)	:68.75	MAKE/MODEL	:TOYOTA/TERCEL
VEHICLE NUMBER	:9650(LAST OF VIN)	ODOMETER	:37125
OPERATOR/DRIVER	:JEFF CARTER	ENGINEER	:D.STEADMAN
COMMENTS	:SITE#1	COMMENTS	:SS/RM
SHIFT DATA TABLE #	:241	REQUESTED INERTIA	:2375 LBS.
REQUESTED ACT HP	:22.8	FUEL TYPE INDEX	:1
ENGINE FAMILY	:HTY1.5V1HFF6	EVAP. FAMILY	:EV-3E
TRANSMISSION TYPE	:4 SPEED	ENGINE DISP/# CYL.	:1.5 LTR./4 CYL.
FUEL SYSTEM	:STREET	TANK CAPACITY	:40%=N/A
TIRE PRESSURE	:45 PSI		

HORSEPOWER

ROADLOAD	19.9
FRONT ROLL FRICTION	2.9
TOTAL	22.8
REAR ROLL FRICTION	.2

THE CORRECT DYNO SETTINGS SHOULD BE 2375LBS. INERTIA AND 19.9 PAU HP

BACKGROUND CONCENTRATIONS

HC	CO	CO2	NOX
4.1630	4.3887	.03275	.31314

REGULAR LOF

****
********** STEADY--STATE TEST **********
****

CO2 TRACER
CARBON AIR TO FUEL RATIO

MD	TIME (S)		HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6	
			---CONCENTRATIONS---						---MODAL GRAMS---														
S	10.0	TP	69.629	42.336	11.52	3.607	.313		.0014	.0018	7.5292	.0002	1.261	10.00	31.9	19.07	-.304	-14.4	-15.7	.1235	-26.2	.3076	
S	10.0	TP	61.486	37.916	11.52	2.903	.312		.0013	.0016	7.5194	.0002	1.260	9.700	31.7	19.08	-.305	-12.8	-15.8	.1135	-26.2	.2938	10 MPH. IN 1ST
S	10.0	TP	48.833	42.071	11.51	2.683	.313		.0010	.0018	7.5394	.0002	1.264	9.800	31.9	19.09	-.310	-13.8	-16.1	.1002	-26.2	.2800	
S	10.0	TP	34.629	42.989	11.92	11.04	.387		.0009	.0022	9.3960	.0008	1.522	9.800	51.5	18.47	-.299	-14.7	-16.6	.1004	-26.1	.2800	
S	10.0	TP	23.994	40.874	11.87	4.175	.382		.0006	.0020	9.2697	.0003	1.507	9.800	52.3	18.55	-.296	-14.4	-15.7	.0878	-26.2	.2668	20 MPH. IN 2ND
S	10.0	TP	32.781	40.675	11.89	6.033	.379		.0008	.0020	9.1972	.0006	1.493	9.700	51.8	18.52	-.307	-13.6	-16.1	.0794	-26.2	.2564	
S	10.0	TP	17.696	41.321	13.09	5.344	.589		.0006	.0029	14.472	.0005	2.134	9.700	58.3	16.91	-.304	-13.6	-15.7	.0909	-26.1	.2671	
S	10.0	TP	21.549	47.605	13.11	22.66	.591		.0008	.0034	14.504	.0023	2.135	9.800	59.2	16.88	-.307	-13.3	-16.8	.0700	-26.2	.2553	35 MPH. IN 3RD
S	10.0	TP	29.481	41.787	13.06	10.37	.580		.0010	.0029	14.241	.0010	2.104	9.700	59.6	16.94	-.301	-13.5	-16.8	.0608	-26.2	.2426	
S	10.0	TP	27.659	41.884	13.41	213.1	.866		.0014	.0042	21.344	.0312	3.071	9.800	57.3	16.52	-.310	-14.3	-16.7	.0768	-26.1	.2522	
S	10.0	TP	15.874	42.800	13.43	64.95	.858		.0008	.0043	21.151	.0094	3.040	9.700	57.0	16.51	-.299	-14.4	-16.0	.0563	-26.2	.2426	50 MPH. IN 4th
S	10.0	TP	16.071	40.600	13.38	126.8	.855		.0008	.0041	21.080	.0184	3.041	9.800	57.6	16.57	-.306	-14.1	-16.7	.0488	-26.2	.2324	

DISTANCE = .9411 MI TP GR/MI .0120 .0351 167.89 .0691 23.83 117.3 53.2 17.76

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********** STEADY--STATE TEST **********
****

CO2 TRACER

CARBON AIR TO FUEL RATIO

MD	TIME (S)		HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6	
			CONCENTRATIONS						MODAL GRAMS														
S	10.0	TP	48.495	40.507	11.43	4.728	.309		.0010	.0017	7.3962	.0003	1.249	10.00	32.6	19.22	-.302	-12.8	-16.7	.1034	-26.2	.3022	
S	10.0	TP	69.576	41.059	11.56	4.850	.318		.0014	.0017	7.6272	.0003	1.273	9.700	31.8	19.01	-.299	-12.7	-15.7	.0815	-26.2	.2892	10 MPH. IN 1ST
S	10.0	TP	70.262	39.759	11.50	8.886	.317		.0015	.0017	7.5957	.0005	1.274	9.800	32.5	19.10	-.294	-12.4	-16.3	.0755	-26.2	.2749	
S	10.0	TP	21.436	46.579	12.40	8.998	.428		.0006	.0025	10.388	.0007	1.616	9.800	47.1	17.79	-.302	-13.8	-16.0	.0767	-26.1	.2795	
S	10.0	TP	18.123	39.841	12.34	6.859	.423		.0005	.0021	10.257	.0005	1.604	9.700	47.2	17.88	-.302	-13.3	-16.8	.0550	-26.2	.2641	20 MPH. IN 2ND
S	10.0	TP	16.289	37.439	12.36	7.866	.420		.0004	.0020	10.212	.0006	1.594	9.700	47.3	17.85	-.299	-12.7	-15.3	.0511	-26.2	.2565	
S	10.0	TP	14.662	43.262	13.31	20.83	.795		.0007	.0040	19.574	.0028	2.837	9.800	43.6	16.64	-.310	-13.3	-16.0	.0576	-26.2	.2703	
S	10.0	TP	19.977	40.512	13.31	13.76	.797		.0009	.0038	19.631	.0018	2.845	9.700	43.2	16.64	-.297	-12.6	-15.2	.0489	-26.2	.2586	35 MPH. IN 3RD
S	10.0	TP	28.669	41.503	13.35	39.65	.777		.0013	.0038	19.131	.0052	2.765	9.800	44.4	16.59	-.305	-12.4	-14.7	.0456	-26.2	.2524	
S	10.0	TP	56.113	1380.4	13.99	222.2	1.56		.0048	.2404	38.323	.0553	5.285	9.700	31.2	15.72	-.300	-13.3	-15.8	.0576	-26.2	.2905	
S	10.0	TP	118.45	5566.3	14.16	355.5	1.59		.0103	.9767	39.049	.0892	5.323	9.700	29.9	15.08	-.304	-12.4	-15.4	.0601	-26.1	.2811	50 MPH. IN 4th
S	10.0	TP	72.325	1579.8	14.25	344.7	1.60		.0063	.2777	39.391	.0866	5.334	9.800	30.8	15.43	-.301	-12.5	-15.9	.0468	-26.2	.2756	

DISTANCE = .9440 MI TP GR/MI .0315 1.608 242.13 .2583 33.00 117.2 36.3 17.25

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********** PARTIAL 75 TEST **********
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CO2 TRACER
CARBON AIR TO FUEL RATIO

MD	TIME (S)	CONCENTRATIONS HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	MODAL GRAMS HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6
K	.8 TP	221.82	25584.	.0736	.4575	.045		.0038	.8839	.03999	.0000	1.048	0.000	.000	76.03	-.301	-14.8	-15.6	.2706	-26.2	.4324
I	20.0 TP	3185.9	50377.	4.569	241.1	.919		.9925	31.66	45.140	.2225	19.07	16.20	1.99	20.78	-.306	-14.0	-15.3	.2647	-26.2	.4221
A	11.0 TP	10500.	109318	6.812	59.28	.636		.8234	17.29	16.941	.0138	4.799	11.00	20.4	10.56	-.300	-13.9	-16.2	.2466	-26.2	.4137
C	84.0 TP	7487.5	99127.	6.910	12.18	.565		3.902	104.2	114.22	.0188	31.90	84.00	25.5	11.43	-.305	-14.3	-16.2	.2204	-26.2	.3823
D	10.0 TP	4729.8	85589.	7.950	8.568	.560		.2535	9.255	13.515	.0014	3.281	10.00	30.5	12.06	-.302	-13.0	-15.8	.1954	-26.2	.3524
CYCLE 1	DISTANCE = 1.146 MI TP						GR/MI	5.206	142.3	165.40	.2234	60.89	121.2	21.9	13.27						
I	38.0 TP	4125.3	67931.	8.909	8.304	.579		.7773	25.82	53.239	.0046	11.53	38.00	1.03	12.96	-.307	-13.0	-15.7	.1893	-26.2	.3404
A	42.0 TP	1923.4	10119.	12.89	132.5	.706		.3427	3.637	72.827	.0699	10.91	37.90	46.6	15.62	-.308	-13.3	-16.1	.1727	-26.2	.3230
C	95.0 TP	307.32	149.59	13.30	145.2	.688		.1168	.1147	160.36	.1635	23.26	94.99	51.8	16.60	-.311	-14.8	-17.8	.1482	-26.2	.2985
D	33.0 TP	91.091	47.772	13.07	23.98	.655		.0116	.0123	52.995	.0091	7.826	28.49	54.6	16.92	-.308	-14.2	-16.2	.1260	-26.2	.2738
CYCLE 2	DISTANCE = 2.060 MI TP						GR/MI	.6062	14.36	164.79	.1200	53.53	199.4	46.9	15.79						
I	13.0 TP	78.983	49.323	13.10	32.87	.662		.0040	.0051	21.130	.0050	3.113	13.00	.659	16.89	-.302	-13.3	-16.3	.1176	-26.2	.2643
A	20.0 TP	77.830	44.237	13.09	33.16	.647		.0060	.0068	31.741	.0075	4.679	17.00	55.3	16.90	-.302	-14.1	-16.0	.1100	-26.2	.2573
C	17.0 TP	73.088	47.016	13.08	28.03	.646		.0047	.0062	26.911	.0054	3.970	0.000	55.6	16.91	-.309	-14.7	-17.2	.1081	-26.2	.2534
D	14.0 TP	75.693	43.772	13.11	40.19	.623		.0039	.0045	21.386	.0061	3.149	11.40	57.5	16.88	-.306	-14.3	-16.2	.1023	-26.2	.2488
CYCLE 3	DISTANCE = .6332 MI TP						GR/MI	.0294	.0357	159.78	.0379	14.91	41.39	55.6	16.90						
I	5.0 TP	72.504	39.921	13.00	26.69	.631		.0014	.0015	7.7425	.0015	1.149	4.999	.628	17.01	-.304	-14.3	-16.1	.0986	-26.2	.2473
A	13.0 TP	66.240	46.102	13.13	33.18	.643		.0033	.0046	20.508	.0048	3.013	13.00	55.6	16.85	-.303	-14.4	-16.4	.0960	-26.2	.2440
D	14.0 TP	58.807	44.223	13.06	17.98	.622		.0030	.0046	21.325	.0027	3.152	14.00	57.1	16.94	-.306	-15.7	-16.2	.0944	-26.2	.2402
CYCLE 4	DISTANCE = .3145 MI TP						GR/MI	.0243	.0340	157.63	.0288	7.314	31.99	56.3	16.91						
I	18.0 TP	66.267	42.807	13.14	32.89	.631		.0044	.0058	27.845	.0065	4.090	18.00	.627	16.84	-.303	-15.3	-15.7	.0916	-26.2	.2356
A	17.0 TP	61.470	41.983	13.13	22.27	.632		.0039	.0054	26.329	.0042	3.871	11.80	56.5	16.86	-.304	-15.4	-16.5	.0851	-26.2	.2303
C	27.0 TP	64.331	39.139	13.12	32.34	.631		.0064	.0079	41.717	.0096	6.136	0.000	56.8	16.87	-.308	-15.5	-16.3	.0872	-26.2	.2279
D	14.0 TP	68.278	39.486	13.15	46.90	.628		.0035	.0041	21.539	.0072	3.162	12.20	57.1	16.84	-.306	-14.1	-15.8	.0864	-26.2	.2227
CYCLE 5	DISTANCE = .7497 MI TP						GR/MI	.0244	.0309	156.64	.0366	17.26	41.99	56.7	16.85						

COLD TRANSIENT MODAL SUMMARY

GRAMS		HC	CO	CO2	NOX	VOL	D/V	DIST	F/E	A/F
IDLE	TP	1.783	58.38	155.	.240	40.0	90.2	.84	57.55	16.60
ACCEL	TP	1.179	20.95	168.	.100	27.3	90.7	1.02	44.16	15.69
CRUISE	TP	4.030	104.35	343.	.197	65.3	179.0	2.21	37.71	14.71
DECEL	TP	.276	9.28	131.	.026	20.6	76.1	.84	51.00	16.33
TOTAL	TP	7.269	192.96	797.	.564	153.1	436.0	4.90	38.79	15.54

EQUIVALENT MASS BAG RESULTS
------------GRAMS/MILE------------

TP	1.482	39.34	163.	.115

01 ENVIRONMENTAL TESTING CORPORATION
STEADY STATE
01 NOV 89 15:51

TEST RUN NUMBER C18714
PRE - TEST

SPEED	:0	TEST NUMBER	:C18714
BARO (MMHG)	:632.3	WET BULB (DEG. F)	:55.82
DRY BULB (DEG.F)	:73.12	MAKE/MODEL	:FORD/THUNDERBIRD
VEHICLE NUMBER	:7380(LAST OF VIN)	ODOMETER	:37087
OPERATOR/DRIVER	:BRIAN WINDECKER	ENGINEER	:D.STEADMAN
COMMENTS	:SITE#1	COMMENTS	:SS/RM
SHIFT DATA TABLE #	:245	REQUESTED INERTIA	:3625 LBS.
REQUESTED ACT HP	:26.7	FUEL TYPE INDEX	:1
ENGINE FAMILY	:N/A	EVAP. FAMILY	:N/A
TRANSMISSION TYPE	:AUTOMATIC	ENGINE DISP/# CYL.	:5.0 LTR./8 CYL.
FUEL SYSTEM	:STREET	TANK CAPACITY	:40%=N/A
TIRE PRESSURE	:45 PSI		

HORSEPOWER	
ROADLOAD	24.0
FRONT ROLL FRICTION	2.7
TOTAL	26.7
REAR ROLL FRICTION	.2

THE CORRECT DYNO SETTINGS SHOULD BE 3625LBS. INERTIA AND 24.0 PAU HP

BACKGROUND CONCENTRATIONS

HC	CO	CO2	NOX
4.5207	4.5465	.03194	.34822

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*********************************************
**********    STEADY--STATE    TEST **********
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*                                           *
*               CO2 TRACER                  *
*       CARBON AIR TO FUEL RATIO            *
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MD	TIME (S)		HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6
			CONCENTRATIONS						MODAL GRAMS													
S	10.0	TP	457.68	872.39	10.26	82.12	1.65		.0572	.2201	40.698	.0296	7.656	10.00	11.8	21.03	-.304	-14.7	-15.6	.1977	-26.2	.4746
S	10.0	TP	285.34	315.09	10.35	86.81	1.63		.0349	.0777	40.097	.0306	7.400	9.800	12.0	21.02	-.306	-14.4	-15.9	.1847	-26.2	.4438
S	10.0	TP	207.84	199.60	10.36	94.41	1.61		.0250	.0485	39.563	.0328	7.371	9.700	12.0	21.04	-.298	-15.2	-15.5	.1609	-26.2	.4181
S	10.0	TP	198.70	71.227	10.66	58.09	1.28		.0186	.0134	31.581	.0157	5.717	9.700	26.6	20.50	-.308	-13.2	-16.0	.1453	-26.2	.4130
S	10.0	TP	184.95	68.539	10.73	53.82	1.30		.0174	.0130	31.994	.0146	5.754	9.800	26.7	20.37	-.310	-14.2	-17.2	.1342	-26.2	.3903
S	10.0	TP	190.24	87.304	10.72	60.34	1.31		.0180	.0166	32.107	.0164	5.779	9.800	26.8	20.38	-.306	-13.9	-15.0	.1255	-26.2	.3705
S	10.0	TP	190.40	104.68	11.57	111.1	1.59		.0203	.0225	39.084	.0341	6.519	9.800	31.3	18.96	-.308	-14.9	-18.0	.1177	-26.2	.3671
S	10.0	TP	176.29	110.53	11.52	108.0	1.58		.0187	.0237	38.762	.0331	6.492	9.800	31.6	19.04	-.313	-14.2	-17.1	.1073	-26.2	.3504
S	10.0	TP	178.66	102.09	11.54	117.1	1.58		.0189	.0218	38.763	.0358	6.485	9.700	31.4	19.02	-.300	-12.5	-17.0	.1112	-26.2	.3439
DISTANCE = .8645 MI		TP						GR/MI	.2649	.5290	384.80	.2808	59.25	88.10	23.0	20.15						

20MPH IN LOW (rows 1–3)

35 MPH IN D (rows 4–6)

50 MPH IN D (rows 7–9)

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********** STEADY--STATE TEST **********
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*   *
*   CO2 TRACER   *
*   CARBON AIR TO FUEL RATIO   *

MD	TIME (S)	HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6	
		CONCENTRATIONS						MODAL GRAMS														
S	10.0 TP	58.644	34.412	9.710	91.71	.794		.0037	.0044	19.349	.0172	3.845	10.00	12.8	22.45	-.298	-13.6	-15.5	.1443	-26.2	.4027	
S	10.0 TP	58.978	32.760	9.689	91.65	.790		.0037	.0041	19.253	.0171	3.835	9.800	12.9	22.49	-.302	-14.7	-16.3	.1325	-26.2	.3804	
S	10.0 TP	60.359	35.512	9.673	90.09	.790		.0038	.0045	19.224	.0168	3.835	9.800	12.9	22.53	-.305	-15.7	-15.4	.1237	-26.2	.3619	10 mph in Low
S	10.0 TP	133.97	321.10	10.52	109.5	1.64		.0162	.0783	40.317	.0394	7.396	9.800	12.2	20.72	-.305	-15.6	-16.1	.1241	-26.2	.3586	
S	10.0 TP	134.74	244.29	10.56	117.6	1.64		.0162	.0594	40.324	.0422	7.372	9.700	12.2	20.67	-.303	-14.2	-16.7	.0988	-26.2	.3413	
S	10.0 TP	115.41	181.77	10.53	122.0	1.64		.0139	.0442	40.296	.0438	7.385	9.800	12.3	20.73	-.309	-13.4	-16.6	.0909	-26.2	.3239	
S	10.0 TP	104.85	201.01	10.56	133.0	1.64		.0126	.0488	40.286	.0476	7.359	9.700	12.2	20.67	-.302	-13.9	-15.7	.0790	-26.2	.3117	20 mph in Low
S	10.0 TP	130.92	88.763	11.41	83.17	1.55		.0138	.0188	38.017	.0260	6.428	9.800	22.5	19.22	-.297	-14.0	-17.0	.0818	-26.2	.3159	
S	10.0 TP	144.63	100.80	11.38	107.1	1.54		.0152	.0213	37.832	.0334	6.414	9.700	22.4	19.27	-.303	-14.1	-16.1	.0740	-26.2	.3033	
S	10.0 TP	132.28	107.11	11.37	99.67	1.55		.0139	.0227	37.887	.0312	6.433	9.800	22.6	19.29	-.309	-15.2	-15.6	.0808	-26.1	.2938	
S	10.0 TP	136.36	97.498	11.37	99.58	1.54		.0143	.0206	37.839	.0311	6.419	9.800	22.6	19.28	-.302	-14.8	-16.0	.0605	-26.2	.2858	35 mph in Drive
S	10.0 TP	154.48	150.26	12.84	276.1	2.57		.0238	.0468	62.822	.1268	9.439	9.800	20.2	17.18	-.311	-13.8	-16.4	.0714	-26.2	.2951	
S	10.0 TP	141.15	180.38	12.81	277.4	2.56		.0217	.0560	62.530	.1271	9.418	9.800	20.3	17.22	-.306	-13.9	-19.7	.0757	-26.2	.2874	
S	10.0 TP	130.65	138.67	12.78	287.4	2.56		.0201	.0431	62.438	.1318	9.425	9.800	20.3	17.26	-.307	-14.5	-15.3	.0679	-26.2	.2792	50 mph in Drive
S	10.0 TP	137.38	127.17	12.81	298.4	2.56		.0211	.0394	62.397	.1364	9.398	9.800	20.3	17.22	-.301	-14.1	-16.2	.0574	-26.2	.2724	

DISTANCE = 1.263 MI TP GR/MI .1695 .4057 491.63 .6872 104.4 146.9 18.0 19.75

01 ENVIRONMENTAL TESTING CORPORATION
STEADY STATE
01 NOV 89 13:11

TEST RUN NUMBER C18708
PRE - TEST

SPEED	:0	TEST NUMBER	:C18708
BARO (MMHG)	:632.6	WET BULB (DEG. F)	:55.23
DRY BULB (DEG.F)	:71.97	MAKE/MODEL	:OLDS/CUTLASS
VEHICLE NUMBER	:2314(LAST OF VIN)	ODOMETER	:65458
OPERATOR/DRIVER	:M.E./J.C.	ENGINEER	:D.STEADMAN
COMMENTS	:SITE#1	COMMENTS	:SS/RM
SHIFT DATA TABLE #	:245	REQUESTED INERTIA	:3375 LBS.
REQUESTED ACT HP	:8.2	FUEL TYPE INDEX	:1
ENGINE FAMILY	:F4G3.8V8XEB3	EVAP. FAMILY	:5B0-4A
TRANSMISSION TYPE	:AUTOMATIC	ENGINE DISP/# CYL.	:3.8 LTR./6 CYL.
FUEL SYSTEM	:STREET	TANK CAPACITY	:40%=N/A
TIRE PRESSURE	:45 PSI		

HORSEPOWER	
ROADLOAD	6.4
FRONT ROLL FRICTION	1.8
TOTAL	8.2

REAR ROLL FRICTION .2

THE CORRECT DYNO SETTINGS SHOULD BE 3375LBS. INERTIA AND 6.4 PAU HP

BACKGROUND CONCENTRATIONS

HC	CO	CO2	NOX
6.5255	4.3247	.03684	.30884

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********** STEADY--STATE TEST **********
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* *
* CO2 TRACER *
* CARBON AIR TO FUEL RATIO *

REGULAR L

MD	TIME		CONCENTRATIONS HC	CO	CO2	NOX	CO2T	O2	MODAL GRAMS HC	CO	CO2	NOX	VOL	D/V	F/E	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6	
	(S)		(PPM)	(PPM)	(%)	(PPM)	(%)	(%)					(F^3)	(SEC)	(MPG)								
S	10.0	TP	73.967	48.807	13.44	86.80	.631		.0027	.0036	15.411	.0093	2.212	10.00	15.3	16.48	-.301	-14.8	-16.3	.2041	-26.2	.2946	
S	10.0	TP	54.180	45.396	13.48	93.65	.656		.0020	.0034	16.022	.0104	2.293	9.800	15.9	16.44	-.302	-12.5	-16.7	.1874	-26.2	.2706	10MPH D
S	10.0	TP	78.891	45.623	14.23	86.99	.606		.0026	.0030	14.815	.0085	2.008	9.800	16.3	15.62	-.308	-13.8	-17.5	.1734	-26.2	.2481	
S	10.0	TP	72.307	49.266	13.99	154.4	.590		.0023	.0032	14.410	.0149	1.988	9.800	33.5	15.88	-.303	-14.0	-15.7	.1549	-26.2	.2408	
S	10.0	TP	74.881	47.499	14.01	145.3	.567		.0023	.0030	13.818	.0134	1.903	9.800	35.5	15.85	-.302	-13.0	-15.2	.1437	-26.2	.2193	20MPH D
S	10.0	TP	73.265	49.866	13.95	153.7	.564		.0023	.0031	13.735	.0142	1.900	9.800	35.3	15.92	-.297	-13.0	-16.1	.1295	-26.2	.2041	
S	10.0	TP	71.015	218.33	14.51	198.0	.990		.0038	.0233	24.340	.0311	3.237	9.800	34.6	15.32	-.310	-14.7	-16.9	.1314	-26.1	.2036	
S	10.0	TP	62.156	96.145	14.51	189.5	.984		.0033	.0102	24.204	.0296	3.219	9.700	34.7	15.34	-.307	-15.2	-17.1	.1040	-26.2	.1879	35MPH D
S	10.0	TP	60.678	48.704	14.43	251.7	.987		.0032	.0052	24.261	.0396	3.244	9.700	34.8	15.42	-.314	-14.1	-16.3	.1105	-26.2	.1756	
S	10.0	TP	44.002	76.032	14.63	835.1	1.27		.0030	.0104	31.322	.1673	4.131	9.800	38.6	15.22	-.302	-14.7	-16.0	.0981	-26.2	.1769	
S	10.0	TP	44.824	62.436	14.63	722.5	1.26		.0030	.0084	31.096	.1436	4.100	9.800	39.1	15.22	-.302	-15.5	-15.4	.0933	-26.2	.1635	50MPH D
S	10.0	TP	50.303	344.88	14.62	745.2	1.25		.0033	.0461	30.736	.1466	4.058	9.800	39.5	15.21	-.303	-12.7	-16.8	.0920	-26.2	.1543	

DISTANCE = .9413 MI TP GR/MI .0359 .1306 270.02 .6676 34.30 117.6 32.9 15.66

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**********   STEADY--STATE    TEST **********
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*                                           *
*               CO2 TRACER                  *
*          CARBON AIR TO FUEL RATIO         *
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TRIPLE

MD TIME (S)	HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6	Note
	---CONCENTRATIONS---						---MODAL GRAMS---														
S 10.0 TP	49.704	41.225	13.81	98.13	.580		.0016	.0027	14.201	.0094	1.985	10.00	16.5	16.08	-.306	-15.4	-15.5	.1550	-26.2	.2404	10 MPH D
S 10.0 TP	57.019	37.010	13.52	90.47	.580		.0019	.0025	14.181	.0080	2.023	9.700	15.7	16.39	-.298	-14.2	-16.2	.1335	-26.2	.2198	
S 10.0 TP	46.415	42.976	12.85	76.07	.572		.0016	.0030	13.956	.0077	2.096	9.800	16.7	17.20	-.307	-14.6	-16.4	.1210	-26.2	.2042	
S 10.0 TP	65.306	44.900	13.98	222.3	.617		.0022	.0031	15.115	.0224	2.086	9.800	31.8	15.89	-.303	-13.7	-16.1	.1117	-26.2	.2031	20 MPH D
S 10.0 TP	53.603	41.280	12.77	131.0	.614		.0020	.0031	14.982	.0143	2.265	9.800	31.3	17.31	-.304	-15.0	-15.0	.1091	-26.2	.1887	
S 10.0 TP	39.298	45.623	12.73	194.5	.577		.0014	.0032	14.064	.0200	2.132	9.800	33.9	17.36	-.303	-14.5	-15.5	.0924	-26.2	.1750	
S 10.0 TP	52.766	204.35	14.66	243.8	1.26		.0035	.0276	31.143	.0403	4.101	9.800	27.0	15.18	-.308	-14.2	-16.1	.0832	-26.2	.1788	35 MPH D
S 10.0 TP	41.744	95.133	14.68	289.7	1.27		.0028	.0129	31.355	.0577	4.122	9.700	26.6	15.17	-.302	-13.9	-14.9	.0794	-26.2	.1700	
S 10.0 TP	39.387	216.52	14.67	292.6	1.28		.0027	.0296	31.560	.0587	4.152	9.700	26.3	15.17	-.301	-13.6	-16.2	.0736	-26.2	.1637	
S 10.0 TP	33.116	276.45	14.88	288.1	2.00		.0034	.0580	49.125	.0887	6.369	9.700	24.3	14.96	-.307	-14.7	-15.9	.0768	-26.2	.1718	50 MPH D
S 10.0 TP	28.376	504.81	14.85	461.5	1.99		.0029	.1056	48.846	.1415	6.347	9.700	24.4	14.97	-.307	-13.4	-16.8	.0700	-26.2	.1618	
S 10.0 TP	40.592	658.44	14.84	160.0	2.00		.0042	.1389	49.219	.0495	6.399	9.800	24.4	14.96	-.303	-14.7	-15.5	.0702	-26.2	.1542	

DISTANCE = .9259 MI TP   GR/MI   .0327 .4214 353.99 .5694 44.08 117.3 25.1 15.89

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********** PARTIAL 75 TEST **********

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CO2 TRACER

CARBON AIR TO FUEL RATIO

	CONCENTRATIONS						MODAL GRAMS								AUX1	AUX2	AUX3	AUX4	AUX5	AUX6
MD TIME (S)	HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F						
K .8 TP	74.521	42417.	.6169	.2386	.068		.0083	.3366	.07698	.0000	.2408	0.000	.000	41.10	-.310	-13.2	-16.4	.4891	-26.2	.7524
I 20.0 TP	4757.4	31086.	8.572	880.0	2.09		1.815	23.92	103.72	1.009	23.35	15.58	2.98	17.55	-.305	-13.1	-15.9	.4833	-26.2	.7347
A 11.0 TP	5267.5	30805.	13.03	1659.	1.65		.5726	6.755	44.935	.5423	6.653	11.00	16.6	13.09	-.307	-13.9	-15.9	.4649	-26.2	.7091
C 84.0 TP	1148.6	2261.5	13.19	1015.	1.41		.8048	3.197	293.06	2.138	42.88	84.00	24.3	16.35	-.305	-14.5	-16.3	.4246	-26.2	.6333
D 10.0 TP	177.64	41.166	12.16	830.7	1.29		.0147	.0069	31.982	.2071	5.075	10.00	27.4	18.10	-.310	-14.7	-16.3	.3851	-26.2	.5661
CYCLE 1 DISTANCE = 1.116 MI TP GR/MI							2.874	30.66	424.57	3.492	78.20	120.5	18.4	16.54						
I 38.0 TP	163.99	53.200	13.12	816.2	1.27		.0469	.0307	118.97	.7018	17.50	38.00	1.27	16.85	-.305	-14.2	-15.8	.3683	-26.2	.5369
A 42.0 TP	138.05	48.020	14.08	982.4	1.22		.0393	.0276	127.07	.8407	17.42	38.10	28.9	15.78	-.307	-13.8	-16.4	.3363	-26.2	.4891
C 95.0 TP	97.244	44.400	13.21	781.6	1.16		.0631	.0581	271.92	1.525	39.72	94.99	30.4	16.75	-.314	-15.3	-17.7	.2935	-26.2	.4183
D 33.0 TP	79.448	42.211	13.07	663.7	1.11		.0173	.0185	90.083	.4336	13.30	28.29	31.9	16.92	-.310	-14.8	-16.2	.2681	-26.2	.3633
CYCLE 2 DISTANCE = 2.040 MI TP GR/MI							.0816	.0661	298.01	1.716	87.94	199.4	29.8	16.60						
I 13.0 TP	75.558	43.822	13.01	644.9	1.09		.0064	.0075	35.152	.1652	5.215	13.00	1.10	17.00	-.307	-13.6	-16.6	.2513	-26.2	.3449
A 20.0 TP	73.173	39.805	13.00	630.8	1.08		.0095	.0104	53.514	.2461	7.943	16.60	32.5	17.01	-.308	-14.5	-16.8	.2391	-26.2	.3338
C 17.0 TP	70.224	41.492	13.01	627.1	1.07		.0077	.0091	45.066	.2059	6.683	0.000	32.8	17.00	-.308	-13.8	-17.1	.2312	-26.2	.3212
D 14.0 TP	68.107	39.420	13.01	621.7	1.07		.0061	.0071	36.872	.1670	5.469	10.90	33.0	17.00	-.306	-14.0	-16.0	.2255	-26.2	.3113
CYCLE 3 DISTANCE = .6266 MI TP GR/MI							.0474	.0546	272.26	1.252	25.31	40.49	32.6	17.00						
I 5.0 TP	66.978	42.430	13.01	636.6	1.06		.0021	.0027	13.119	.0609	1.946	4.999	1.06	17.00	-.305	-12.2	-15.3	.2221	-26.2	.3085
A 13.0 TP	65.916	40.547	13.00	633.0	1.05		.0054	.0067	33.857	.1563	5.026	13.00	33.4	17.01	-.303	-14.6	-16.6	.2196	-26.2	.3006
D 14.0 TP	64.081	42.454	12.76	536.7	1.04		.0057	.0076	35.832	.1428	5.417	14.00	33.0	17.31	-.306	-13.8	-16.0	.2137	-26.2	.2908
CYCLE 4 DISTANCE = .3127 MI TP GR/MI							.0423	.0544	264.79	1.151	12.39	31.99	33.5	17.14						
I 18.0 TP	62.407	39.483	12.74	533.7	1.03		.0071	.0090	45.900	.1823	6.952	18.00	1.03	17.34	-.307	-13.0	-16.0	.2046	-26.2	.2816
A 17.0 TP	60.887	39.214	12.75	558.0	1.03		.0065	.0085	43.281	.1795	6.549	11.20	33.9	17.32	-.308	-13.9	-16.5	.1956	-26.2	.2706
C 27.0 TP	59.009	38.627	12.72	544.2	1.03		.0100	.0133	68.669	.2785	10.41	0.000	34.0	17.36	-.309	-14.2	-17.0	.1858	-26.2	.2550
D 14.0 TP	57.529	39.213	12.70	519.4	1.03		.0051	.0070	35.588	.1379	5.406	11.80	34.2	17.39	-.307	-14.0	-17.0	.1758	-26.2	.2434
CYCLE 5 DISTANCE = .7403 MI TP GR/MI							.0388	.0510	261.31	1.051	29.32	40.99	34.0	17.35						

COLD TRANSIENT MODAL SUMMARY

GRAMS		HC	CO	CO2	NOX	VOL	D/V	DIST	F/E	A/F
IDLE	TP	1.878	24.31	317.	2.120	55.2	89.5	.81	40.25	17.31
ACCEL	TP	.633	6.81	303.	1.965	43.6	89.9	1.01	28.42	16.14
CRUISE	TP	.886	3.28	679.	4.147	99.7	179.0	2.18	28.25	16.69
DECEL	TP	.049	.05	230.	1.088	34.7	75.0	.83	32.09	17.21
TOTAL	TP	3.445	34.44	1529.	9.320	233.2	433.4	4.84	26.96	16.78

EQUIVALENT MASS BAG RESULTS

----------GRAMS/MILE----------

TP	.712	7.12	316.	1.927

01 ENVIRONMENTAL TESTING CORPORATION
STEADY STATE
01 NOV 89 10:52

TEST RUN NUMBER C18706
PRE - TEST

SPEED	:0	TEST NUMBER	:C18706
BARO (MMHG)	:634.3	WET BULB (DEG. F)	:55.38
DRY BULB (DEG.F)	:69.91	MAKE/MODEL	:VOLKSWAGON/BUS
VEHICLE NUMBER	:#4279(LAST OF VIN)	ODOMETER	:47346
OPERATOR/DRIVER	:JEFF CARTER	ENGINEER	:CSU
COMMENTS	:SITE#1	COMMENTS	:SS/RM
SHIFT DATA TABLE #	:241	REQUESTED INERTIA	:3875 LBS.
REQUESTED ACT HP	:16.0	FUEL TYPE INDEX	:1
ENGINE FAMILY	:N/A	EVAP. FAMILY	:N/A
TRANSMISSION TYPE	:4 SPEED	ENGINE DISP/# CYL.	:1.2 LTR./4 CYL.
FUEL SYSTEM	:STREET	TANK CAPACITY	:40%=N/A
TIRE PRESSURE	:45 PSI		

HORSEPOWER

ROADLOAD	13.5
FRONT ROLL FRICTION	2.5
TOTAL	16.0
REAR ROLL FRICTION	.2

THE CORRECT DYNO SETTINGS SHOULD BE 3875LBS. INERTIA AND 13.5 PAU HP

BACKGROUND CONCENTRATIONS

HC	CO	CO2	NOX
6.5379	3.7063	.03046	.32674

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********** STEADY--STATE TEST **********
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CO2 TRACER
CARBON AIR TO FUEL RATIO

MD	TIME (S)		HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6	
			CONCENTRATIONS						MODAL GRAMS														
S	10.0	TP	3405.7	18205.	13.26	193.4	.796		.1590	1.714	19.638	.0272	2.857	10.00	10.6	14.23	-.308	-13.8	-15.[illegible]	.4274	-26.2	1.555	10 MPH. IN 1ST
S	10.0	TP	2985.8	17723.	13.31	194.7	.799		.1397	1.673	19.751	.0275	2.863	9.800	10.6	14.28	-.295	-13.0	-14.7	.4038	-26.2	1.499	
S	10.0	TP	3649.0	17385.	13.26	198.2	.795		.1704	1.638	19.637	.0279	2.858	9.800	10.6	14.30	-.301	-14.1	-15.2	.3667	-26.2	1.447	
S	10.0	TP	2578.2	19062.	13.55	349.7	1.01		.1501	2.239	25.022	.0614	3.564	9.800	17.0	13.99	-.302	-12.9	-15.0	.3370	-26.2	1.401	20 MPH. IN 2ND
S	10.0	TP	2531.5	18084.	13.51	302.0	.965		.1411	2.034	23.886	.0508	3.412	9.800	17.4	14.12	-.301	-15.0	-15.0	.3150	-26.2	1.343	
S	10.0	TP	2467.8	18569.	13.52	306.6	.974		.1388	2.106	24.112	.0520	3.441	9.800	17.2	14.07	-.297	-12.1	-15.3	.2940	-26.2	1.288	
S	10.0	TP	2549.5	16852.	13.78	940.1	1.32		.1914	2.552	32.804	.2128	4.594	9.800	22.7	14.01	-.297	-12.4	-16.1	.2686	-26.2	1.235	35 MPH IN 3RD
S	10.0	TP	2614.1	17195.	13.75	935.3	1.31		.1948	2.585	32.504	.2102	4.560	9.800	22.9	14.00	-.301	-12.4	-14.7	.2584	-26.2	1.169	
S	10.0	TP	2655.8	17988.	13.72	846.7	1.27		.1924	2.629	31.516	.1850	4.434	9.800	23.2	13.95	-.315	-13.7	-15.1	.2343	-26.2	1.106	
S	10.0	TP	2903.7	24375.	13.36	1973.	1.87		.3158	5.348	46.070	.6471	6.656	9.700	21.7	13.62	-.304	-13.6	-16.2	.2194	-26.2	1.052	50 MPH. IN 4th
S	10.0	TP	2857.8	25038.	13.36	1936.	1.80		.2986	5.278	44.279	.6104	6.396	9.800	22.5	13.56	-.310	-13.4	-16.5	.2046	-26.2	.9819	
S	10.0	TP	2818.7	24539.	13.33	1960.	1.82		.2992	5.254	44.877	.6276	6.496	9.800	22.4	13.63	-.302	-13.1	-16.7	.1884	-26.2	.9184	

DISTANCE = .9386 MI TP GR/MI 2.546 37.34 387.92 2.919 52.13 117.7 19.5 13.98

TEST RUN NUMBER C18777

PRE - TEST

START PHASE	:1	END PHASE	:1
TEST NUMBER	:C18777	BARO (MMHG)	:631.5
WET BULB (DEG. F)	:52.71	DRY BULB (DEG.F)	:7[illegible].63
MAKE/MODEL	:DODGE/RAM 50	VEHICLE NUMBER	:8165-PJ
ODOMETER	:87364	OPERATOR/DRIVER	:MIKE CARTER
ENGINEER	:STEADMAN	COMMENTS	:SITE#1
COMMENTS	:HS05(COLD)	SHIFT DATA TABLE #	:241
REQUESTED INERTIA	:3000	REQUESTED ACT HP	:11.4
FUEL TYPE INDEX	:1	ENGINE FAMILY	:N/A
EVAP. FAMILY	:N/A	TRANSMISSION TYPE	:5 SPEED
ENGINE DISP/# CYL.	:2.6 LTR/4 CYL	FUEL SYSTEM	:CLEAR
TANK CAPACITY	:40%=N/A	TIRE PRESSURE	:45 PSI

HORSEPOWER

ROADLOAD	9.8
FRONT ROLL FRICTION	1.6
TOTAL	11.4
REAR ROLL FRICTION	.2

THE CORRECT DYNO SETTINGS SHOULD BE 3000LBS. INERTIA AND 9.8 PAU HP

:

BACKGROUND CONCENTRATIONS

HC	CO	CO2	NOX
4.7840	5.9276	.03434	.47959

START TIME: 15:30:36 CRANK TIME: .95 S

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PARTIAL 75 TEST

CO2 TRACER
CARBON AIR TO FUEL RATIO

MD TIME (S)	HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6
	CONCENTRATIONS						MODAL GRAMS													
K 1.0 TP	11.059	25202.	.0900	.5371	.044		.0002	.5917	.33670	.0006	.0301	0.000	.000	77.12	.0265	1.072	.0021	.2063	-26.1	.1304
I 20.0 TP	4360.2	71249.	.7773	5.492	.082		.4585	15.39	2.5877	.0016	6.424	0.000	.562	23.11	.0714	-5.25	.0007	.0380	-26.2	.1270
A 11.0 TP	10422.	61506.	2.182	12.97	.210		.7460	11.70	4.9507	.0026	4.386	0.300	.000	17.14	.0309	4.503	-.001	-.107	-26.1	.1297
C 64.0 TP	10422.	112430	4.313	17.58	.664		10.24	222.8	134.40	.0465	68.13	21.00	0.38	11.64	.0211	6.774	-.000	-.016	-42.0	-.015
D 10.0 TP	10422.	100566	5.183	17.74	.371		.5514	11.59	0.6971	.0026	3.230	0.000	13.5	11.46	.0344	4.200	-.001	-.092	-41.7	-.207
CYCLE 1 DISTANCE = .5310 MI TP GR/MI							22.59	493.4	263.78	.1042	75.01	30.30	7.06	14.44						
I 30.0 TP	10422.	106379	6.362	31.64	.394		1.021	37.51	35.261	.0155	10.70	0.000	1.07	10.99	.0050	9.256	.000	.015	-26.3	-.264
A 42.0 TP	9104.3	98604.	7.063	215.0	1.11		4.169	63.69	114.19	.2763	20.02	0.000	18.3	11.41	.0292	5.434	.0002	.0365	-45.6	-.306
C 95.0 TP	3744.6	30420.	11.92	772.1	1.63		3.778	70.20	381.45	2.107	61.76	0.000	23.9	13.39	.0367	3.990	.0000	.0000	-64.1	-.922
D 33.0 TP	1397.5	394.47	10.10	334.3	.432		.1372	.1765	31.425	.6921	6.007	0.000	75.4	21.15	.0614	-.254	.0004	-.340	-47.2	-1.45
CYCLE 2 DISTANCE = 1.963 MI TP GR/MI							5.045	101.6	266.39	1.309	106.5	0.000	19.2	13.78						
I 13.0 TP	727.15	642.65	11.40	68.82	.240		.0146	.0260	7.3095	.0039	1.229	0.060	.230	18.92	.0106	11.72	-.000	-.017	-26.1	-1.42
A 29.0 TP	1244.0	6064.0	12.70	603.5	1.40		.2113	2.670	62.412	.3231	13.40	0.000	15.3	16.41	.0137	0.320	.0006	.1377	-42.0	-1.30
C 17.3 TP	907.90	6450.3	14.22	476.4	1.25		.1140	1.513	52.573	.1555	7.109	0.000	27.1	14.83	.0665	-2.27	.0001	-.002	-53.1	-1.44
D 14.0 TP	1179.2	536.56	12.69	210.2	.522		.0520	.0477	17.735	.0260	2.690	0.000	39.0	17.18	.0679	.2744	-.000	-.097	-43.4	-1.49
CYCLE 3 DISTANCE = .3603 MI TP GR/MI							1.066	7.753	345.90	1.545	21.45	0.000	21.4	16.57						
I 5.0 TP	1016.6	2000.0	4.017	51.93	.179		.0120	.0511	1.9263	.0010	.7717	0.000	.166	41.64	.0407	1.692	-.001	-.123	-26.7	-1.47
A 15.6 TP	917.79	7714.5	11.63	610.4	1.30		.1100	1.723	44.417	.2671	7.371	0.000	12.5	17.52	.0167	6.650	.000	.030	-40.0	-1.45
D 14.3 TP	1349.2	775.46	13.05	632.9	.593		.0657	.0762	20.157	.0665	2.901	0.000	34.2	16.60	.0010	12.13	.0001	.0601	-42.7	-1.47
CYCLE 4 DISTANCE = .1462 MI TP GR/MI							1.295	14.42	454.95	2.034	11.12	0.000	15.5	26.92						
I 10.3 TP	710.32	973.75	9.000	65.20	.230		.0212	.0305	0.5021	.0055	1.023	0.000	.175	23.70	.0110	10.73	.0001	.3494	-26.3	-1.41
A 17.0 TP	999.46	6667.4	12.78	857.4	1.61		.1659	2.240	66.551	.3774	10.16	0.000	13.6	16.37	.0066	11.26	.0004	.1179	-43.4	-1.56
C 27.0 TP	736.12	8523.9	14.20	434.4	1.12		.1213	2.760	74.171	.2006	10.00	0.000	29.7	14.60	.0248	7.763	.0006	.1342	-53.0	-1.45
D 14.3 TP	1007.3	550.16	12.30	179.7	.479		.0415	.0457	16.065	.0207	2.520	0.000	30.4	17.70	.0207	7.939	.0009	.1409	-41.6	-1.51
CYCLE 5 DISTANCE = .4429 MI TP GR/MI							.7097	11.54	373.61	1.414	24.50	0.000	22.5	17.75						

COLD TRANSIENT MODAL SUMMARY

GRAMS		HC	CO	CO2	NOX	VOL	D/V	DIST	F/E	A/F
IDLE	TP	2.329	53.42	56.	.036	21.3	0.0	.00	97.16	19.35
ACCEL	TP	5.403	101.71	299.	1.270	60.3	9.3	.60	11.16	14.58
CRUISE	TP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	21.0	[illegible]	17.58	[illegible]
DECEL	TP	.948	11.93	94.	.228	17.4	0.0	.54	41.96	18.05
TOTAL	TP	22.834	472.40	1071.	4.116	238.6	30.3	3.45	16.10	15.36

EQUIVALENT MASS BAG RESULTS
---------GRAMS/MILE---------

TP	6.615	136.35	316.	1.193

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TEST SUMMARY 3:45 PM WED., 15 NOV., 1989

PRE - TEST

START PHASE	:1	END PHASE	:1
TEST NUMBER	:C18777	BARO (MMHG)	:631.5
WET BULB (DEG. F)	:52.71	DRY BULB (DEG.F)	:73.63
MAKE/MODEL	:DODGE/RAM 50	VEHICLE NUMBER	:8165-PJ
ODOMETER	:[illegible]	OPERATOR/DRIVER	:MIKE CARTER
ENGINEER	:STEADMAN	COMMENTS	:SITE01
COMMENTS	:H505(COLD)	SHIFT DATA TABLE #	:241
REQUESTED INERTIA	:3000	REQUESTED ACT HP	:11.4
FUEL TYPE INDEX	:1	ENGINE FAMILY	:N/A
EVAP. FAMILY	:N/A	TRANSMISSION TYPE	:5 SPEED
ENGINE DISP/# CYL.	:2.6 LTR/4 CYL	FUEL SYSTEM	:CLEAR
TANK CAPACITY	:40%=N/A	TIRE PRESSURE	:45 PSI

	HC	CO	CO2	NOX	F/E
TLPIPE GRAMS PHASE 1	22.834	472.399	1090.903	4.118	16.097
PHASE					
SAMPLE CONC. PHASE 1	984.839	5296.832	.880	37.148	
PHASE					
BKGND. CONC. PHASE 1	14.559	3.102	.034	.589	
PHASE					
MDL. COR. GR PHASE 1	.371	7.238	20.796	.076	
PHASE					
BAG GRAMS PHASE 1	38.776	429.248	1086.627	4.120	
PHASE					
BAG GR/MI PHASE 1	11.231	124.325	314.725	1.193	16.281
PHASE					

TEST PARAMETER	PHASE 1
DRIVER VIOLS. (SEC.)	30.3
NOX-CORR FACTOR	.8465
DILUTION FACTOR	8.883
CVS VOLUME (FT3)	2418.434
AVE CVS PRES. (MMHG)	623.8
AVE CVS TEMP (DEG. F)	77.4
ACTUAL DIST (MI.)	3.450
AUXILLIARY SIGNAL #1	.030
AUXILLIARY SIGNAL #2	5.492
AUXILLIARY SIGNAL #3	.000
AUXILLIARY SIGNAL #4	.014
AUXILLIARY SIGNAL #5	-44.660
AUXILLIARY SIGNAL #6	-.801

01 ENVIRONMENTAL TESTING CORPORATION
STEADY STATE
01 NOV 89 17:14

TEST RUN NUMBER C18717
PRE - TEST

SPEED	:0	TEST NUMBER	:C18717
BARO (MMHG)	:631.7	WET BULB (DEG. F)	:54.88
DRY BULB (DEG.F)	:72.12	MAKE/MODEL	:CHEV/PU 1970
VEHICLE NUMBER	:3591(LAST OF VIN	ODOMETER	:53446
OPERATOR/DRIVER	:BRIAN WINDECKER	ENGINEER	:D.STEADMAN
COMMENTS	:SITE#1	COMMENTS	:SS/RM
SHIFT DATA TABLE #	:245	REQUESTED INERTIA	:3000 LBS.
REQUESTED ACT HP	:24	FUEL TYPE INDEX	:1
ENGINE FAMILY	:N/A	EVAP. FAMILY	:N/A
TRANSMISSION TYPE	:4 SPEED	ENGINE DISP/# CYL.	:6 CYL
FUEL SYSTEM	:STREET	TANK CAPACITY	:40%=N/A
TIRE PRESSURE	:45 PSI		

HORSEPOWER	
ROADLOAD	22.1
FRONT ROLL FRICTION	1.9
TOTAL	24.0
REAR ROLL FRICTION	.2

THE CORRECT DYNO SETTINGS SHOULD BE 3000LBS. INERTIA AND 22.1 PAU HP

BACKGROUND CONCENTRATIONS

HC	CO	CO2	NOX
6.3990	19.510	.03606	.40264

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********** STEADY--STATE TEST **********

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CO2 TRACER

CARBON AIR TO FUEL RATIO

MD	TIME (S)		CONCENTRATIONS HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	MODAL GRAMS HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6	
S	10.0	TP	2296.6	24437.	12.61	107.5	.762		.1065	2.287	18.554	.0147	2.839	10.00	10.8	14.29	-.298	-14.9	-15.7	.1571	-26.2	.3825	
S	10.0	TP	2355.0	24921.	12.86	105.0	.760		.1068	2.280	18.503	.0141	2.776	9.700	10.9	14.02	-.307	-12.7	-15.4	.1409	-26.2	.3693	
S	10.0	TP	2276.3	24648.	12.89	106.8	.762		.1033	2.257	18.562	.0143	2.778	9.800	11.1	14.03	-.303	-13.0	-15.5	.1366	-26.2	.3514	10 mph 1st
S	10.0	TP	3370.7	25818.	13.10	303.7	.999		.1983	3.064	24.437	.0527	3.600	9.800	16.4	13.65	-.304	-14.1	-16.0	.1228	-26.2	.3441	
S	10.0	TP	3116.2	33369.	13.08	276.8	.994		.1826	3.944	24.315	.0479	3.586	9.800	15.7	13.02	-.307	-13.9	-16.1	.1270	-26.2	.3324	
S	10.0	TP	3068.0	32673.	13.14	285.9	.998		.1798	3.862	24.419	.0495	3.586	9.800	15.7	13.04	-.301	-13.9	-15.2	.1125	-26.2	.3216	20 mph 2nd
S	10.0	TP	3492.6	32290.	13.17	815.2	1.20		.2449	4.568	29.300	.1688	4.292	9.800	23.2	13.02	-.308	-14.1	-15.7	.1026	-26.2	.3133	
S	10.0	TP	3496.1	31249.	13.14	830.3	1.20		.2453	4.424	29.251	.1720	4.295	9.700	23.3	13.12	-.311	-13.4	-17.1	.1029	-26.2	.3040	
S	10.0	TP	3484.0	31459.	13.18	825.7	1.20		.2437	4.440	29.251	.1705	4.282	9.700	23.3	13.08	-.306	-12.3	-15.8	.0928	-26.2	.2958	35 mph 4th
S	10.0	TP	3099.9	17911.	13.56	2261.	2.41		.4244	4.946	58.890	.9137	8.378	9.700	18.2	14.04	-.301	-13.6	-15.9	.0976	-26.1	.2977	
S	10.0	TP	3177.5	18196.	13.54	2277.	2.39		.4319	4.990	58.392	.9140	8.319	9.700	18.3	14.02	-.304	-14.3	-16.6	.0807	-26.2	.2887	
S	10.0	TP	3168.2	17801.	13.54	2295.	2.40		.4326	4.904	58.619	.9254	8.357	9.800	18.5	14.07	-.302	-13.3	-17.4	.0744	-26.2	.2776	50 mph 4th

DISTANCE = .9584 MI TP GR/MI 3.026 47.96 409.54 3.608 57.09 117.3 18.0 13.62

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********** STEADY--STATE TEST **********

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CO2 TRACER

CARBON AIR TO FUEL RATIO

			------------CONCENTRATIONS-----------						------MODAL GRAMS-------														
MD	TIME (S)		HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6	
S	10.0	TP	2237.7	22795.	12.89	118.2	.789		.1051	2.160	19.199	.0164	2.875	10.00	10.9	14.22	-.301	-13.9	-15.8	.2206	-26.2	.4649	
S	10.0	TP	2128.0	22453.	12.99	119.2	.796		.1001	2.131	19.382	.0165	2.879	9.800	10.9	14.18	-.302	-13.3	-16.[illegible]	.2012	-26.2	.4407	10 MPH 1ST GEAR
S	10.0	TP	2130.8	22384.	12.99	120.4	.793		.0998	2.115	19.286	.0166	2.866	9.800	10.9	14.19	-.311	-13.8	-15.[illegible]	.1984	-26.2	.4211	
S	10.0	TP	2807.3	24281.	13.22	281.4	1.02		.1672	2.918	24.983	.0494	3.646	9.800	16.0	13.75	-.309	-14.9	-15.7	.1834	-26.2	.4137	
S	10.0	TP	2818.6	25644.	13.15	279.0	1.02		.1682	3.086	24.876	.0491	3.651	9.700	15.9	13.68	-.310	-13.4	-15.[illegible]	.1748	-26.2	.3932	20 MPH 2ND GEAR
S	10.0	TP	3705.6	36248.	13.03	272.1	1.01		.2206	4.353	24.593	.0478	3.644	9.700	15.0	12.77	-.307	-12.7	-16.[illegible]	.1561	-26.2	.3790	
S	10.0	TP	3252.9	28496.	13.15	514.7	1.03		.1956	3.456	25.082	.0913	3.680	9.800	27.7	13.38	-.306	-12.2	-16.[illegible]	.1575	-26.2	.3764	
S	10.0	TP	3273.8	29834.	13.14	480.3	1.02		.1954	3.592	24.870	.0845	3.653	9.700	27.7	13.27	-.305	-14.8	-15.[illegible]	.1487	-26.2	.3627	
S	10.0	TP	3256.2	24376.	13.17	467.5	1.02		.1935	2.922	24.818	.0819	3.637	9.800	29.1	13.74	-.301	-14.2	-15.[illegible]	.1374	-26.2	.3475	35 MPH 4TH GEAR
S	10.0	TP	3469.6	34752.	12.90	1227.	1.59		.3303	6.675	38.969	.3446	5.827	9.700	23.9	13.00	-.307	-13.6	-15.[illegible]	.1319	-26.2	.3489	
S	10.0	TP	3447.8	34024.	12.89	1263.	1.58		.3268	6.505	38.739	.3531	5.801	9.800	24.4	13.08	-.308	-12.6	-15.[illegible]	.1215	-26.2	.3318	
S	10.0	TP	3457.1	34375.	12.94	1225.	1.58		.3257	6.532	38.651	.3403	5.765	9.800	24.5	13.01	-.309	-13.2	-16.[illegible]	.1192	-26.2	.3192	50 MPH 4TH GEAR

DISTANCE = .9509 MI TP GR/MI 2.554 48.85 340.16 1.569 47.92 117.4 20.9 13.52

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********** STEADY--STATE TEST **********

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CO2 TRACER

CARBON AIR TO FUEL RATIO

MD	TIME (S)		HC (PPM)	CO (PPM)	CO2 (%)	NOX (PPM)	CO2T (%)	O2 (%)	HC	CO	CO2	NOX	VOL (F^3)	D/V (SEC)	F/E (MPG)	A/F	AUX1	AUX2	AUX3	AUX4	AUX5	AUX6
			CONCENTRATIONS						MODAL GRAMS													
S	10.0	TP	7075.7	108814	7.482	61.97	.762		.5471	16.97	18.347	.0141	4.732	10.00	18.0	10.48	-.297	-14.4	-17.5	.1783	-26.2	.4199
S	10.0	TP	7295.9	109462	7.312	54.43	.744		.5625	17.83	17.880	.0124	4.719	9.700	18.1	10.51	-.302	-13.5	-17.5	.1690	-26.2	.4019
S	10.0	TP	7466.0	109798	7.226	51.46	.741		.5796	17.19	17.790	.0118	4.751	9.800	18.1	10.52	-.297	-13.3	-16.0	.1538	-26.2	.3842
S	10.0	TP	4954.0	85773.	10.37	189.0	1.00		.3666	12.80	24.348	.0412	4.529	9.700	19.1	10.69	-.303	-12.5	-16.3	.1664	-26.2	.3955
S	10.0	TP	5266.1	82672.	9.810	157.8	.971		.3988	12.63	23.563	.0352	4.635	9.700	19.5	11.16	-.304	-13.0	-16.7	.1467	-26.2	.3768
S	10.0	TP	5210.1	83084.	9.887	157.6	.967		.3900	12.55	23.476	.0347	4.582	9.700	19.6	11.10	-.308	-13.8	-15.5	.1385	-26.2	.3604

DISTANCE = .5786 MI TP GR/MI 4.917 154.1 216.75 .2582 27.95 58.60 18.7 10.74

35 MPH

35 MPH