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Project Summary

Evaluation of a Remote Sensor for Mobile Source CO Emissions

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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 nonattainment problem.

This project summary was developed by EPA's Environmental Monitoring Systems Laboratory, Las Vegas, NV, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

This project report describes an EPA-sponsored evaluation of a device designed to measure the carbon monoxide (CO) emissions from a passing automobile by means of remote sensing. The University of Denver developed the device with support from the Colorado Office of Energy Conservation as an approach to promote improved vehicle fuel economy. High CO emissions are indicative of incomplete fuel combustion caused by out-of-adjustment or defective fuel and emission systems. Surveillance for CO emissions will identify vehicles with potential fuel efficiency benefits if repaired. As a result of this original purpose, the CO emissions monitoring system is called FEAT, for Fuel Efficiency Automobile Testing.

The FEAT, shown schematically in Figure 1, consists of three basic units: an infrared (IR) light source, an IR detector and a personal computer. IR absorption is used to determine the amounts of CO and CO_2 emitted by a passing automobile. The IR light source, located on one side of a roadway, sends a collimated beam into a gas filter radiometer equipped with two liquid-nitrogen-cooled indium antimonide photovoltaic detectors. A 4.3 micron filter isolates the CO region before one of the two detectors. The resulting beam passes through a rotating gas filter wheel, half of which contains a CO and H_2 mixture and the other half N_2. The rotating wheel modulates the signal and provides both a reference channel and a CO data channel.

The system is installed across a single-lane highway with the IR beam located at

Carbon Monoxide Remote Sensing

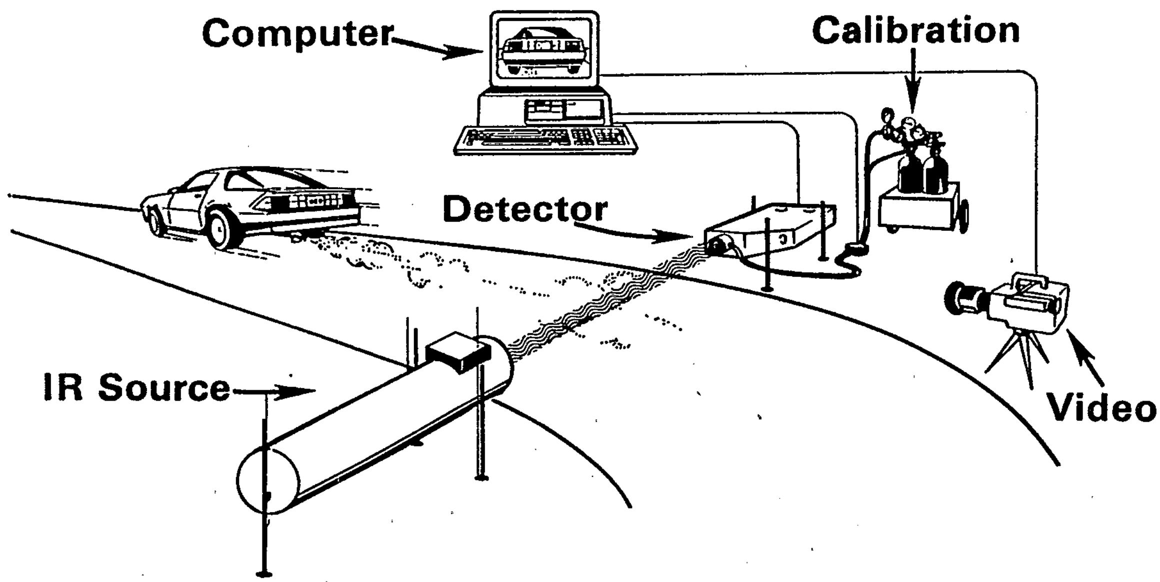

Figure 1. Schematic diagram of the University of Denver CO remote sensor.

the height of most exhaust pipes (about 25 centimeters above the pavement). When a vehicle enters the optical path a drop in reference voltage signals the vehicle's presence. Span voltages from each of the three signal channels (CO, CO_2, and reference) are acquired before the vehicle enters the beam, and zero correction voltages for each channel are acquired while the vehicle is completely blocking the beam. As the vehicle exits the beam, a one half second voltage versus time trace from each of the three channels is obtained.

The voltage values obtained as a vehicle exits the beam are corrected for the ambient measurements obtained in front of the vehicle. Voltages are converted to path-averaged concentrations with a linear calibration equation. Calibration constants are determined periodically while in use by measurements of certified compressed gas mixtures to allow path-averaged CO and CO_2 concentrations to be determined. The concentrations of the CO and CO_2 in the exhaust plume change jointly as they rapidly disperse in the turbulent wake behind the vehicle. The computer calculates a ratio of CO to CO_2 that corresponds to the slope of a best fit line for a scatter plot of these two gases. The confidence limits of the slope must be better than 20% for the software to accept the measurement as valid.

Using the combustion reaction equations, the ratio of CO to CO_2 is converted to exhaust percent CO. The results are stored on floppy disk and printed on a video tape together with a freeze-frame video image of the rear of the vehicle at a rate as fast as one vehicle per second. At some locations emissions measurements of over one thousand vehicles per hour have been made.

The remainder of this document summarizes the evaluation of the FEAT. It is organized in four sections which correspond to the objectives of the project. These objectives are:

1. to evaluate the theory used to convert the CO to CO_2 ratio to percent CO and to grams CO per gallon of fuel;
2. to validate the theory using existing data from laboratory-grade gas monitors;
3. to inter-compare FEAT and laboratory-grade emissions measurements of vehicles on a dynamometer; and
4. to discuss potential applications for remote sensing of vehicle emissions.

Theory

The FEAT depends on the carbon and oxygen balances of the combustion reaction equations to convert the measured CO to CO_2 ratio into percent CO and grams CO per gallon of fuel burned. This entails certain assumptions concerning the chemical formula for the fuel and the presence of unburned hydrocarbons. Complete derivation of the theory used by FEAT and an analysis of the sensitivity of the FEAT results to the required assumptions is the subject of this part of the evaluation project.

The conversion equation from the measured ratio to exhaust percent CO depends on a knowledge of the carbon to hydrogen ratio in the fuel. However the error introduced by assuming a typical value is very small, particularly for low emission vehicles (less than 4% CO). About 70% of the vehicles measured by FEAT have percent CO emissions of less than 1% CO. Even considering a very high CO emitting vehicle with the most extreme cases of fuel carbon to hydrogen ratios, 1:0 for pure carbon (e.g., coal) and 1:4 for methane, the FEAT reported percent CO of 8.8 would be 26% low for the coal-fired vehicle and 33% high for the methane vehicle.

When FEAT readings are converted to mass emissions in grams CO per gallon of fuel, hydrocarbon emissions may either be neglected, or corrected using an average hydrocarbon emissions factor. In either case the corrections are small, particularly for the low emission vehicles. For most vehicles (i.e., about 95%) the uncorrected grams CO per gallon values are within 6% of the corrected values.

Presently under development is a hydrocarbon remote sensing monitoring channel for FEAT which will eliminate this small source of inaccuracy when reporting grams CO per gallon of fuel. This hydrocarbon channel will also enable remote sensing to report hydrocarbon exhaust emissions directly.

Theory Validation

Ratios of CO to CO_2 from conventional exhaust system probe measurements can be directly compared to FEAT measurements of the ratio. However, a direct comparison of percent CO can not be done without correcting the probe value for dilution air. Dilution of vehicle exhaust by air which is not part of the combustion process (e.g., as introduced by an air pump) results in a lower CO concentration at the probe. FEAT exhaust measurements are unaffected by dilution air. Probe readings are adjusted upwards to take into account any dilution caused by the excess air by using the probe exhaust oxygen (O_2) measurement as an indicator. Unless stated otherwise, all exhaust probe results used in comparisons have been adjusted with the oxygen correction for dilution air.

A data set obtained from the Chrysler Corporation allowed a FEAT-independent evaluation of the FEAT theory. Measurements included real-time CO, CO_2, and O_2 vehicle emissions concentrations before and after an exhaust system catalyst. The malfunctioning vehicle was operated on a dynamometer for the test. Catalyst efficiency was near 100% for low percent CO emissions but dropped to about 50% when presented with high percent CO emissions. The same equations that FEAT uses for calculation of percent CO where applied to the ratio of CO to CO_2 calculated from the Chrysler data.

Figure 2 shows the resulting FEAT theory calculated percent CO (the lines) compared to the Chrysler measured percent CO (the boxes and X's). The agreement is excellent, except for a slight inability of the FEAT theory to respond completely to the highest CO peaks, which may be due to lags in laboratory instrumentation. The FEAT theory applies as well after the catalyst as before it, indicating that the catalyst follows the same combustion reaction equation as the engine.

Dynamometer Testing

An interface was required which would enable the FEAT unit to measure the emissions from a vehicle on a dynamometer since the normal FEAT mode of operation requires a passing vehicle to trigger its measurement cycle. The interface consisted of a system for compressing raw exhaust into a two liter stainless steel canister from which there were two exits. At the bottom of the canister a small leak eliminated the water which had condensed, and maintained ventilation of the tubing. At the side of the canister a short tube led through a computer controlled solenoid valve to a ring of holes normally used as the intake for calibration gas to the FEAT system. A small rotating blade was used to simulate the presence of a vehicle and to trigger the release of exhaust into the beam. Since the blade rotated every two seconds, a reading of the exhaust was available every two seconds when the FEAT was operated in this mode. The hardware and software were otherwise identical to those used by the FEAT during normal on-road operation.

Comparison testing was performed at the Environmental Testing Corporation (ETC), a private automobile emissions testing facility that specializes in high altitude certification tests for several automobile manufacturers. ETC is equipped with dynamometer facilities, constant volume sampling systems, and a full suite of exhaust gas analytical instrumentation.

Tests were conducted on November 1, 1989 and November 15, 1989. Single blind and double blind test protocols were employed to compare FEAT to laboratory CO measurements. The majority of the tests were conducted in a steady-state mode where a vehicle on a dynamometer was allowed to stabilize at a specific speed for a specific load prior to calling for the measured values from the FEAT and ETC monitors. In one test, the emissions from a cold vehicle were monitored as the vehicle warmed up, thus allowing the changing emissions from the period before, during, and after catalyst warm-up to be monitored. In that test, O_2 data from ETC was unavailable to allow dilution correction to their values.

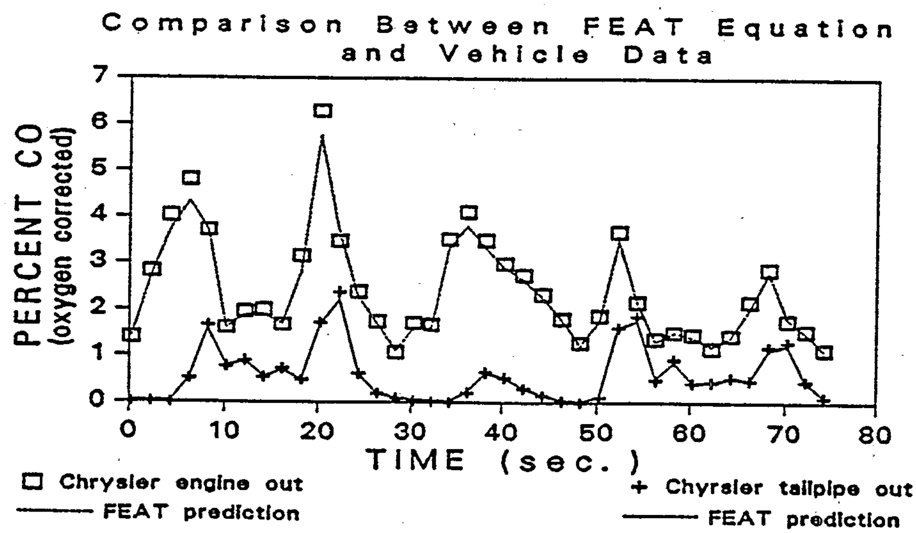

Figure 2. Chrysler data on a malfunctioning vehichle. Upper line is the FEAT equation prediction from the engine emissions. Points are the oxygen corrected data. Lower line and points are the equivalent data from the tailpipe.

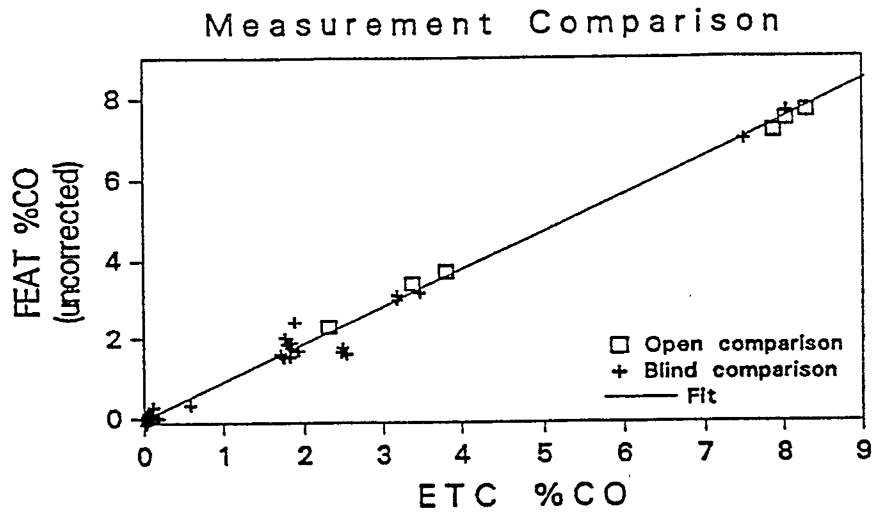

Figure 3. Uncorrected FEAT readings against ETC readings. Blind comparisons conducted 11/1/89 and 11/15/89. Open comparison data obtained on 11/15/89 is dilution corrected. All data not corrected for calibration cylinder discrepancies.

Figure 3 is a scatter graph of the FEAT- and ETC-measured percent CO along with a best fit line for the steady state tests. The slope of the line is 0.94, the intercept 0.011% CO and the R^2 is 0.99. The FEAT data are reported as raw data. If the calibration data are used from the day on which the measurements were taken, the FEAT readings would be increased by a factor of approximately 1.04. For the non-steady-state test the vehicle started at CO levels too high for ETC to read, then as the engine and catalyst warmed up the emissions decreased to very low values. Comparison for this test also showed agreement between the two approaches.

The agreement between the FEAT and laboratory-grade instrument indicates that the FEAT correctly measures the instantaneous emissions of on-road vehicles. Precision was determined to be better than one third of one percent CO for a range of measured emissions up to greater than ten percent CO.

Possible Applications

FEAT has been shown to make fast and accurate measurements of the instantaneous CO emissions from vehicles as they pass by the instrument. Broadly speaking, this technology has application for characterization of CO emissions from individual vehicles or characterization of fleet CO emissions by aggregation of individual measurements.

The value of individual vehicle monitoring is the identification of the small fraction of the vehicles that are responsible for the majority of the mobile emissions (i.e., roughly 20% of the vehicles produce 60% of the emissions). Fleet emissions characterization might produce improved emissions input for air quality predictive models, or more quickly identify a subset of the fleet with systematic failures that can be addressed through actions such as recall or tampering investigations. However, to fully realize specific applications requires additional research. This section discusses some of the applications of the technology and the associated issues which must be addressed. Vehicle emissions are variable and depend upon many factors including engine/control system condition, vehicle load, driving mode (e.g., rate of acceleration/ deceleration, etc.), and engine and catalyst temperature. The traditional approaches for emissions monitoring attempt to minimize the variations by controlling the influential factors. The Federal Test Procedure (FTP), which is used to certify new vehicle emissions, does this by making integrated emissions measurements on vehicles operated on a dynamometer under very carefully controlled conditions during a prescribed operating and vehicle load cycle. The FTP emission measurements are on a mass basis as opposed to volume concentration measurements. Though considerably less well controlled than the FTP, most Inspection and Maintenance (I & M) programs use steady-state tests conducted on warmed engines under idle and fast idle, no-load conditions. I & M emissions are measured on a volume concentration basis. The present new vehicle emission control standards and the maintenance requirements for the on-road fleet are designed to be responsive to these two test procedures.

The remote sensor has less control over, or capability to monitor the factors which influence emissions than the traditional approaches. In addition, it makes a "snap shot" type of measurement which could catch a vehicle during an anomalous point in its emission cycle. Judicious selection of the monitoring location will allow some control over load as influenced by road grade and position with respect to road conditions (i.e., highway entrance or exit ramps) and traffic signs (i.e. stop signs). Use of radar (recently integrated into the FEAT data system) will permit vehicle driving mode to be monitored.

The remote sensor has two powerful advantages over the traditional approaches. It measures emissions of vehicles as they are in the real-world, under load in which a traditional I & M test does not. A single system can make thousands of measurements per day in a cost efficient way.

Fleet and individual vehicle applications have different monitoring requirements. For fleet monitoring applications, the large data sets that can be easily gathered make the aggregated results immune from errors resulting from emission variability, though still subject to any bias resulting from non-representative emissions conditions. If bias cannot be sufficiently minimized or determined, it could prevent intercomparisons between emissions in different parts of the country. However, bias would have little effect in the intercomparison in relative terms of various segments of the same fleet (e.g., vehicle age, make and model, etc.) monitored at a single location and time. Individual vehicle monitoring is subject to both emissions bias and variability. It should be possible to minimize variability by selection of monitoring sites that increase the chances of a vehicle being in a steady-state mode of operation. Similarly, bias may be controlled by picking monitoring locations that will result in representative emissions. Multiple measurements of the same vehicle is another approach to decrease problems caused by variability.

There are a number of possible goals that could be established as part of an individual vehicle monitoring program. Obvious gross emitting vehicles could be required to improve emissions through repair or adjustment; vehicles with high test results could be subject to additional tests; or obviously clean vehicles could be given an exemption from periodic I & M tests. Research is required to establish the remote sensor measurement value that corresponds to the action level desired.

Notice

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The complete report, entitled "Evaluation of a Remote Sensor for Mobile Source CO Emissions," (Order No. PB91-148 320/AS; Cost: $17.00, subject to change) will be available only from:
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