IR Long-Path Photometry: A Remote Sensing Tool for Automobile Emissions

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Picture Los Angeles or New York City on a hot summer day. Few commuters can ignore the ever-present haze surrounding these cities caused by motor vehicles that emit carbon monoxide (CO), hydrocarbons, nitrogen oxides, fine particles, and lead. With the Clean Air Act of 1970 and subsequent amendments (1,2), a mandate exists "to protect and enhance the quality of the Nation's air resources." As a result, a major industry concerned with the measurement of automobile exhaust emissions was born.

After reviewing the Federal Motor Vehicle Control Program, M. J. Walsh (3) outlined the following criteria for an as-yet nonexistent ideal emissions test. It should evaluate the vehicle under real-life conditions; be reproducible, accurate, quick, and inexpensive; measure all pollutants of concern; and be comprehensive enough to discourage testing bias.

From a scientific standpoint, it is essential that the first criterion be met. With this in mind, we undertook a new approach using an old technology to develop a long-path IR photometer that can remotely measure CO emissions from operating vehicles.

Current testing

Federal and state governments, along with the automobile manufacturers, test and certify new vehicle emissions and carry out some in-use testing of older vehicles. These tests use the Federal Test Procedure (FTP) (4–7), a carefully designed, specific test that is divided into cold transient, cold stabilized, and hot transient phases. A vehicle is operated under a series of accelerations, decelerations, stops, and starts on a chassis dynamometer whose inertia and friction are set for each vehicle. The emissions from each phase are collected at a constant volume into three sample bags, and the concentrations of each species are determined.

The final result, given in grams of pollutant per mile, is a weighted average from the three phases. The driving course is modeled after a typical summertime (20 °C to 30 °C) commute to work in Los Angeles. Each test takes at least 12 h to complete and costs more than $700. Precision of the results for a given vehicle is claimed to be ±20% (8) and is controlled mainly by the reproducibility of the automobile's emission system, not by the test system or gas analysis protocols.

Current computer models (EPA MOBILE3 and soon-to-be-released MOBILE4) are based on the concept that the FTP emissions measured from a fleet of vehicles are well correlated (though not necessarily 1:1) with the emissions that the same fleet would exhibit under normal driving conditions. Because little is known about actual on-the-road fleet emissions, it is impossible to gauge the accuracy of this assumption.

The public is more familiar with state inspection and maintenance (I/M) programs, which are designed to test every vehicle in any area with air
pollution problems. These I/M tests are always less rigorous than the FTP, and thus the results are less indicative of actual on-the-road emissions. The most sophisticated centralized I/M testing programs use a chassis dynamometer with one or two fixed loads and speeds and measure the steady-state emissions as a percent of the exhaust. Many centralized (and all decentralized) programs only measure idle emissions at one, or possibly two, engine speeds. These tests typically take 10–15 min to perform and cost $6 to $12 each.

Remote sensing instrumentation

The idea of remotely measuring vehicle emissions is not new. Lockheed Missiles and Space Corporation first attempted to construct an across-the-road monitor for the California Air Resources Board (9), but successful operation of the device was never reported. Later, Chaney (10) proved that CO plumes from passing cars could be observed using a gas filter correlation radiometer. Unfortunately, Chaney's system did not include any of the parameters necessary to estimate emissions data from the plume observation.

The University of Denver's instrument consists of three basic units: the source, a detector, and a computer. IR absorption is used to determine the amounts of CO and CO₂ 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 (Judson Infrared Inc., Montgomeryville, PA). A 4.3-μm bandpass filter isolates the CO₂ spectral region, and a 4.6-μm filter isolates the CO region. The 4.6-μm beam passes through a rotating gas filter wheel (Thermo Environmental Corp., Franklin, MA), one-half of which contains a CO and H₂ mixture and the other half N₂ (11). The rotating wheel modulates the signal and provides both a reference channel and a CO data channel. Figure 1 is a schematic of the optics and the detector layout.

A typical operational scenario follows. The system is installed across a single-lane highway with the IR beam located 10 in. (25.4 cm) above the roadway. When a car enters the optical path, a drop in the reference voltage signals the vehicle's presence. Span voltages from each of the three signal channels (CO₂, CO, and reference) are acquired before the car enters the beam, and zero correction voltages for each channel are acquired while the car is completely blocking the beam. As the vehicle exits the beam, a 1-s voltage versus time trace from each of the three channels is obtained. The 1 s is a user-selected time chosen for convenience; recent tests of one-half second of exhaust plume have also been successful. The signal is averaged over 8 ms (the time for one-half of a rotation of the gas filter wheel), zero-corrected, and related to the span values.

Figure 2a shows a typical 1-s voltage trace for the CO, CO₂, and reference channels. If a second vehicle enters the beam and interrupts the measurement...
of a previous vehicle, the software recycles and performs the measurement on the new vehicle using the span values obtained from in front of the first car.

Emission results are obtained by computing the ratios of the CO and CO\textsubscript{2} voltages (I) to the reference voltages (I\textsubscript{ref}) and re-scaling these arbitrary units into calibrated CO and CO\textsubscript{2} values through the use of calibration curves determined in the laboratory (see Figure 2b). These data are then analyzed by a least-squares procedure that determines a single path-independent CO/CO\textsubscript{2} ratio from the slope of the CO versus CO\textsubscript{2} graph in Figure 2c.

It has been well documented that the application of a linear least-squares analysis to data whose dependent and independent variables are both subject to error can produce erroneous results (12, 13). As a safeguard, some on-road experimental data were fitted using the linear least-squares method and a standard iterative nonlinear procedure (14). All of these tests produced identical measurements of the slope within experimental error.

The CO/CO\textsubscript{2} ratio is the only valid measurement that can be made because the instrument cannot distinguish the magnitude or position of the exhaust plume. Pollution contribution can be determined directly from the ratio. A high ratio corresponds to a high polluter, a low ratio to a clean-burning vehicle. The highest polluters observed produce almost vertical slopes.

Computer algorithms are written conservatively; confidence limits require the presence of minimum amounts of CO\textsubscript{2}, and slope standard deviations must not exceed ±20%. The minimum amount of CO\textsubscript{2} requirement is used to distinguish cars from pedestrians, bicycles, or heavy-duty trucks with elevated exhaust systems. When tests are made in favorable weather, data fall outside these confidence limits for less than 10% of the measurements.

**Conversion of CO/CO\textsubscript{2} ratio to exhaust percent CO**

Most workers in the automobile emissions field do not report CO/CO\textsubscript{2} ratios. Idle emission standards are usually written in terms of percent CO. Thus we have derived equations that translate the observed CO/CO\textsubscript{2} to the percent CO that an exhaust gas monitor would observe if inserted into the tailpipe at the time of the remote sensing measurement. We also have derived the equation for converting the CO/CO\textsubscript{2} ratio into grams of CO per gallon of fuel, an important conversion for fleet studies.

These calculations are made under the assumption that any excess air present in the exhaust is neglected and that the contribution of water vapor to the actual exhaust volume is subtracted. This is analogous to standard moni-

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**Figure 2.** (a) Data from the remote sensor for a 1983 Oldsmobile at 20 mph, (b) raw data converted to calibrated CO and CO\textsubscript{2} values vs. time using a 4-in. (10.16 cm) calibration cell, and (c) the final CO/CO\textsubscript{2} correlation graph used to obtain unitless slope. Clean cars produce a horizontal correlation graph.
tors that measure a reading after the water vapor has been condensed out of their intake systems. Figure 3 shows an ideal engine map of percent emissions as a function of air-to-fuel ratio (15). Above the standard diagram is the same information plotted in terms of the ratio of emitted species to CO₂. The equations are derived from an accurate version of this diagram and the standard chemical equation for combustion in air of a 6:1 by weight carbon:hydrogen mixture typical of Denver gasoline.

**Accuracy and precision**

The sensor is calibrated initially using a special flow cell with calcium fluoride windows and a 4-in. (10.16-cm) optical path. Controlled mixtures of pure CO and CO₂ mixed with nitrogen are passed through the cell using mass flow controllers (MKS Instruments Inc., Andover, MA). The calibration is checked in a mode that simulates auto exhaust by momentarily blocking the beam and then puffing certified mixtures of CO and CO₂ for half a second into the beam without the cell.

At a local freeway ramp, three certified gas mixtures with CO/CO₂ ratios of 1:12.1, 1:1, and 4.96:1 (Scientific Gas Products, Longmont, CO; and Linde, Denver, CO) were used for field calibration. The 1:12.1 cylinder was measured 61 times over a temperature range of 5 °C to 26 °C with a mean and standard error of 0.103 ± 0.01; the 1:1 cylinder was measured 53 times over a temperature range of −2 °C to 24 °C with a mean and standard error of 1.017 ± 0.091; and the 4.96:1 was measured 27 times over a temperature range of 6 °C to 21 °C with a mean and standard error of 4.91 ± 0.88. These ratios, translated into exhaust percent CO values, would be 1.44 ± 0.13 (1:12.1), 8.84 ± 0.46 (1:1), and 16.27 ± 0.68 (4.96:1). The system is calibrated daily using the gas mixtures and an automated computer program.

In the summer of 1987 three vehicles were tested under similar conditions (i.e., warmed up and in first gear under constant acceleration in a large circular parking lot). Each vehicle was driven a constant 20 mph up a 3% grade and was measured 31 times by the sensor. Measurement variability was found to increase with increasing CO concentration. A computer-controlled, low-mileage 1985 Chevy Celebrity gave results of 0.22 ± 0.4% CO. A 1981 Honda Civic with California-specified controls and high mileage gave results of 1.84 ± 0.4% CO. This vehicle emitted less than 1% CO when idling and experienced transient emissions of up to 6% CO when shifting into second gear. A 1987 Ford Galaxie showed the highest emissions and variability at 6.47 ± 0.9% CO.

Further testing was conducted on the Honda Civic at a local speedway. Measurements were made at speeds of up to 40 mph with the gear ratio, speed, and manifold vacuum recorded. An attempt was made to simulate these conditions on a chassis dynamometer at the Environmental Testing Corporation in Aurora, CO. Unfortunately, on the dynamometer it was impossible to sufficiently reduce the inevitable dynamometer roller load on the vehicle to obtain identical manifold vacuums. With this caveat in mind, the dynamometer laboratory results summarized in Table I can be compared with the field data.

A 1977 Volkswagen Bus was equipped with an on-board Peerless Corporation exhaust gas monitor and printer to measure percent CO and percent CO₂. Tests were conducted at vari-

![Table I](image)

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<th>Percent CO</th>
<th>No. of readings</th>
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<td>Remote sensor at Bandimere Speedway</td>
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* Not applicable.
ous air-to-fuel ratios on a local freeway ramp. Figure 4 compares the results between the two monitors. One experimental difficulty encountered was that the intake system for the Peerless monitor created a 13-s delay between the tailpipe and the actual measurement. Because the printer was operated manually, the timing of this delay could account for the values at the higher air-to-fuel ratios exceeding the expected ±1% error bounds. More “high-end” calibration data and a vehicle whose emissions can be adjusted to higher percent CO’s are needed to extend the range. Typical in-use percent CO emissions range from 0% to 16%. Based on the test data described above, we believe that our system has an accuracy and precision of ±1% CO for an individual test.

Comparison to Federal Test Procedure

In collaboration with the Colorado Department of Health, a comparison between the FTP and our remote sensing method was attempted. After the lengthy FTP was completed, each vehicle was driven up a parking lot with a grade of ~2.5% through the remote sensor beam. An average of three to five readings was recorded. Fifty-three measurements were recorded for 30 vehicles that consumed either regular unleaded or oxygenated fuels. A correlation coefficient to the FTP of 0.71 was obtained. Using only the first remote sensing measurement from each vehicle, the correlation coefficient to FTP is 0.58. First and second measurements from three vehicles—a 1986 and a 1987 Dodge Aries and a 1987 Isuzu Pickup—were excluded from the correlations because of unexplained behavior in which high (~2-5%) initial percent CO measurements were followed by very low measurements (~0-0.5%). The variability observed in the remote sensing test results was comparable to the variability of the standard two-speed idle tests performed by the Colorado Department of Health concurrent with the FTP tests. Direct variability comparisons with FTP were not possible because the FTP measurements were not repeated.

Using miles-per-gallon data available from the FTP tests, it is possible to convert our percent CO (grams of CO per gallon of fuel) readings directly into grams of CO per mile, improving the average correlation to 0.81. This data set indicates that further improvement in the correlation is possible through the use of a multimode test (i.e., using different speeds and acceleration rates) (16). Because remote sensing fulfills the need for a direct on-road test, correlation with FTP is not as important as it is for short-cycle dynamometer tests.

Applications and future developments

The University of Denver’s remote sensor allows the rapid and low-cost measurement of numerous vehicles operating under real conditions. Figure 5 is a histogram detailing the CO measurements of 20,725 vehicles made during a
two-week period in April 1988 at a local freeway ramp. A small percentage of the vehicles are very high CO emitters. In this data set 8.6% of the vehicles account for half of the CO emissions, and 71% of the vehicles are totally irrelevant contributors from an air quality standpoint (all measured at less than 1% CO). This demonstrates the ease with which very large data sets can be accumulated at a fraction of the cost of current testing.

Currently under development is a video system that will enable us to ask more pertinent questions of our fleet distributions: What is the day-to-day variability of the high-pollution vehicles, and can they be repeatedly identified? What do percent CO distributions look like for various vehicle ages and models (e.g., are the high-polluting vehicles all older vehicles)? Do some models have a higher probability of showing up in this category?

The EPA computer model has been shown to be ineffective at predicting operating vehicle emissions. In two recent studies (17, 18), the EPA model of vehicle CO emissions (MOBILE3) was in error by more than a factor of two. The MOBILE# models are handicapped by a lack of operating vehicle data, especially on “super emitters” (vehicles with CO emissions greater than 150 grams per mile). We anticipate that remote sensing measurements can form the basis for a more realistic model through the collection of large in-use databases (19, 20).

The current device will work only on a single lane of traffic and on only one exhaust species, CO. It probably will not be possible to distinguish separate contributions from vehicles operating in adjacent lanes. However, we believe that the basic concept is sound and that it is feasible to expand the sensor to monitor additional species such as hydrocarbons, formaldehyde, and nitrogen oxides.

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References
(2) Clean Air Act as Amended 1977, 42 U.S.C. Sec. 7503.
(4) Fed. Regist. 1986, 21(61), Part II.
(7) Fed. Regist. 1971, 36(128), Part II.

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