ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **46**: 343-348

Prediction of IM240 Mass Emissions Using Portable Exhaust Analyzers

Paul L. Guenther, Donald H. Stedman, and Jon M. Lesko
University of Denver, Denver, Colorado

ABSTRACT

Inspection and maintenance programs for motor vehicles in the United States increasingly use loaded mode mass emissions testing (IM240). A method was developed to predict mass emission rates and mass emission changes, particularly from repair benefits, using a low-cost, portable four-gas non-dispersive infrared (NDIR) vehicle exhaust gas analyzer. A single vehicle was tested several times with the analyzer while on the dynamometer and undergoing successive repairs. Excellent correlations for CO and HC were observed. Five vehicles were measured using an on-road driving loop before and after emissions-related repairs, while another three vehicles were tested with no repairs performed. The on-road concentration data used to guide the repair process were converted to grams per gallon; when divided by estimated miles per gallon, this gave grams per mile emissions for comparison to IM240. Correlation coefficients (r^2) of 0.87 for CO and 0.76 for HC were achieved for the 13 tests. The linear correlations between IM240 and emissions measured by this method would allow repair facilities to perform a relatively inexpensive test for diagnostic purposes and to estimate repair effectiveness without the need for a dynamometer.

IMPLICATIONS

A low-cost, portable exhaust gas analyzer was tested using a fixed driving loop, and was shown to give results which are proportional to more complex loaded-mode emission inspection (IM240) readings. The results are diagnostically useful in themselves, and can enable repair shops to determine that their repairs will pass the "after-repair" IM240 test.

INTRODUCTION

The City of Denver in December 1990 enacted an Alternative Fuels Ordinance (No. 330) that requires businesses operating vehicle fleets of ten or more vehicles to convert 10% of that fleet to run on alternative fuels such as compressed natural gas (CNG) or propane (LPG).[1] The University of Denver (DU) requested and was granted a temporary waiver from the ordinance for the purpose of demonstrating an alternative emissions reduction strategy. The approach was to use a remote sensor to identify those faculty, staff, and student vehicles with high levels of carbon monoxide (CO) as they arrived on campus in the morning, and to reduce those emissions through repair.

The remote sensing instrument is capable of measuring the carbon monoxide (CO) and hydrocarbon (HC) emissions of vehicles in less than a second as the vehicle drives past it. The instrument is a non-dispersive infrared (NDIR) device, designed to emulate the emissions readings one would observe had the vehicle been equipped with an exhaust probe from a traditional exhaust gas analyzer inserted in its tailpipe.[2-6]

Remote sensors were set up at the entrances to DU parking lots to measure arriving commuter vehicles for exhaust emissions screening. At most locations, the remote sensing test observed vehicles in low-speed (near idle) driving modes. Drivers of vehicles with exhaust %CO readings greater than 3.5% were approached for possible participation in the repair program. Chassis dynamometer testing was used before and after repair to quantify the emissions benefit.

The chassis dynamometer test used was the IM240, which is a 240-second transient driving cycle in which emissions for CO, HC, carbon dioxide (CO_2), and oxides of nitrogen (NO_x) are determined on a gram per mile basis. Tests were performed at the National Center for Vehicle Emissions Control and Safety (NCVECS), a laboratory grade dynamometer facility located in Fort Collins, Colorado, a 120 mile round trip from Denver. The dynamometer's analyzers use NDIR for CO and CO_2, flame ionization detection for HCs, and chemiluminescence for NO_x.

After making several unproductive trips to Fort Collins with vehicles that either had not been properly repaired or were not suitable for repair, a local loaded-mode testing method was developed. Available to us were two portable four-gas NDIR analyzers, a Model No. 3400 supplied by OTC (655 Eisenhower Drive, Owatonna, MN 55060-1171) and a PGA 9000 manufactured by MPSI (6405 19 Mile Road, Sterling Heights, MI 48314-2115). These instruments allowed us to collect and store second-by-second data of a vehicle's CO, HC, CO_2, and O_2 exhaust emissions concentrations. This study shows that the portable analyzers provided data which were very useful in guiding repairs, in predicting IM240 readings, and in verifying repair benefits. The fact that useful correlations can be obtained between an instrument costing a few thousand dollars and a dynamometer system costing over $100,000 has considerable implications for smaller repair shops.

EXPERIMENTAL

Before the initial use of the portable analyzer, the instrument was calibrated using a gas mixture consisting of 9.98% CO_2, 1.99% CO, and 2010 ppm propane, with a balance of nitrogen prepared to a tolerance of ±2% by Scott Specialty Gases (500 Weaver Road, Longmont, CO 80501). This same gas had been used to calibrate the remote sensors to identify the high emitters. During the first few weeks of use, the portable analyzer's calibration was checked for stability against the calibration cylinder with every use. The instrument readings were always within the 2% tolerance of the calibration gases. These calibrations were checked several months later and found to be quite stable. This cylinder was not compared to the cylinders used to calibrate the IM240 system.

The first step in using the portable analyzers was to establish a driving loop designed to include the vehicle operating modes of an IM240. The driving loop most often used ran 5.1 miles, took about 15 minutes to complete, and incorporated-stop-and go driving, 30-40 mph cruise speeds, and some 50-55 mph highway driving. The vehicle was driven after a fifteen-minute warm-up period at idle, using whatever fuel was in the tank. The loop time was determined for each measurement using the internal computer clock, and the vehicle's odometer was used for the distance driven. Software external to that normally supplied with the analyzers was used to collect the data in ASCII form, since at the time neither analyzer had built-in software allowing us to store the amount of data needed. Running external software meant interfacing the analyzers with a portable battery-powered, laptop computer.

After a vehicle was identified as a high emitter with remote sensing, an on-road test was performed using a portable analyzer. The analyzer's optical bench was warmed up in the lab by operating the instrument for at least 30 minutes prior to installing the analyzer in the vehicle. The diagnostic software provided by Andros ran on our portable PC; used with the OTC analyzer, it provided complete command/control over analyzer functions. This software allowed us to shut the analyzer off, relocate it to the vehicle, turn it back on, and not have to repeat the warm-up cycle. The analyzer was powered from the vehicle's 12V system (via the cigarette lighter outlet) and the probe was routed out of the passenger compartment and into the tailpipe. The analyzer exhaust hose (and, when practical, the analyzer drain line) were vented outside the vehicle. A typical installation took one person about 10 to 15 minutes, during which time the vehicle was warming up at idle.

The vehicle was then driven through the prescribed route. After completing the driving loop, the ASCII data files were imported into a spreadsheet program for analysis. Applying the same mathematics used in the remote sensing system, the second-by-second grams per gallon emissions were calculated by using the $\%CO/\%CO_2$ and $\%\text{propane}/\%CO_2$ ratios from the exhaust gas analyzer. The equations are:[5]

$$\%\ \text{propane} = \frac{\text{ppm hexane}}{0.518 \cdot 10{,}000} \tag{1}$$

$$\text{grams CO/gallon} = \frac{5506{*}\%CO}{\%CO + \%CO_2 + 3{*}\%HC} \tag{2}$$

$$\text{grams HC/gallon} = \frac{8644{*}\%HC}{\%CO + \%CO_2 + 3{*}\%HC} \tag{3}$$

The 0.518 in Equation 1 is related to the propane to hexane conversion (commonly referred to as PEF, for propane equivalency factor) and is specific for each analyzer. The number will vary slightly, usually between 0.5 and 0.52, dependent upon small differences in the wavelength bandpass of the filter used on the HC detector.

The grams per gallon data were then averaged and divided by an estimate of miles per gallon (mpg) fuel consumption. Fuel consumption has been successfully estimated in previous studies attempting to correlate concentration measurements to mass emissions.[7] We used two inputs to estimate fuel economy. The vehicle owner was the preferred source, but most did not record their mileage (which might explain how they were able to drive such high-emitting vehicles without knowing it); otherwise, CAFE (corporate average fuel economy) data for 1980 and newer vehicles were used in a simplified formula to predict fuel economy. The 1980 CAFE standard of 24 mpg was also used for the pre-1980 vehicles. Use of the CAFE standard with adjustments for engine size resulted in consistent mpg estimation for each vehicle. Application of the formula results in a reduction of the CAFE standard by 25% for a six-cylinder engine and 40% for an eight-cylinder engine. The fuel economy values derived in this manner were consistently 10% to 15% lower than the IM240 measured fuel economy. Incomplete combustion of gasoline results not only in higher CO output, but it also causes the fuel to produce less energy. More fuel must be consumed to travel a given distance and, thus, fuel economy suffers as vehicle CO emissions increase. The estimated fuel economy figures from the formula were then adjusted for the average %CO content of the exhaust using the following formula:[8]

$$\text{Adjusted mpg} = \text{Estimated mpg} - \text{Estimated mpg}{*}\,\frac{\%CO{*}2}{100} \tag{4}$$

For example, an 18 mpg six-cylinder with an average exhaust CO concentration of 5% would have an adjusted mpg of 18 - (18*0.10) or about 16 mpg. For prediction of repair effectiveness, the actual fuel economy of the vehicle matters less than the consistent use of a formula.

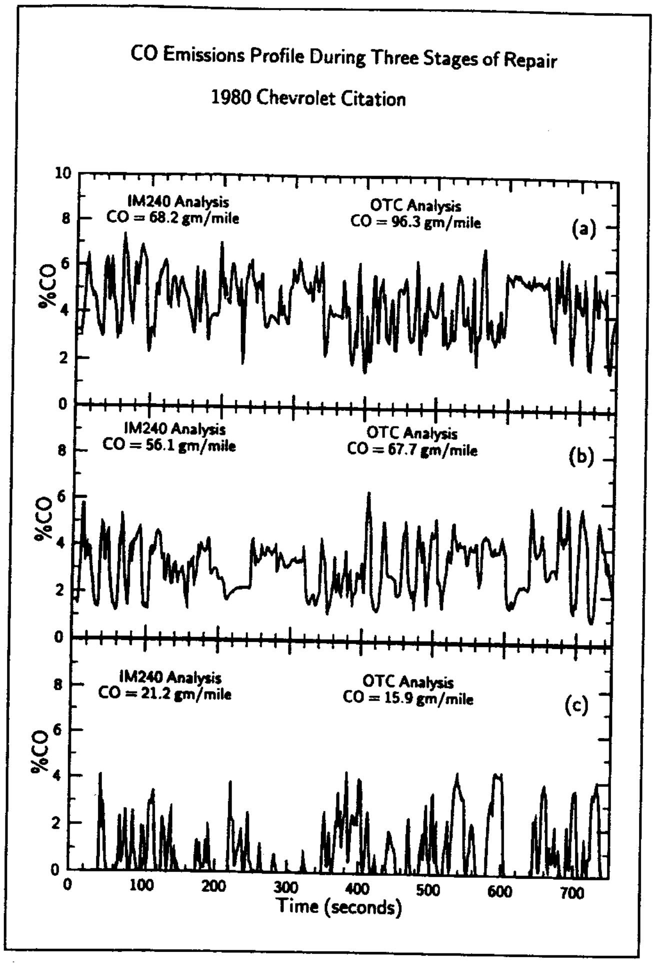

Figure 1. Second-by-second %CO emissions traces during three stages of repair of a 1980 Chevrolet Citation 2.8L; (a) initial measurement, (b) after first repair, (c) after final repairs. OTC refers to the portable analyzer used. The mass emissions are derived from the observed trace. Comparison IM240 tests were taken at the same stage of repair, but not usually on the same day.

Dividing the measured average grams per gallon value for the drive cycle by the estimated miles per gallon resulted in a grams per mile estimate which was then compared to the IM240 test performed on the same vehicle at the same stage of repair. The IM240 tests were performed within a few days of the on-road measurements.

RESULTS

A 1984 Nissan Sentra was given incremental repairs with its emissions being monitored simultaneously between each repair step using both IM240 and a portable analyzer. For this one test vehicle, the four-gas analyzer collected its data while the vehicle was undergoing IM240 testing. During seven IM240s, repeated after each stage of repair was completed, the driving cycle was the same, vehicle variability (between drive cycles) was eliminated, and average fuel economy was known. Excellent linear correlations were observed for both CO and HC. For CO the slope was 0.86 and the r^2 was 0.99. For HC the equivalent parameters were 0.47 and 0.98, respectively. While the slopes of the lines are not unity, the linear correlation coefficients were excellent.

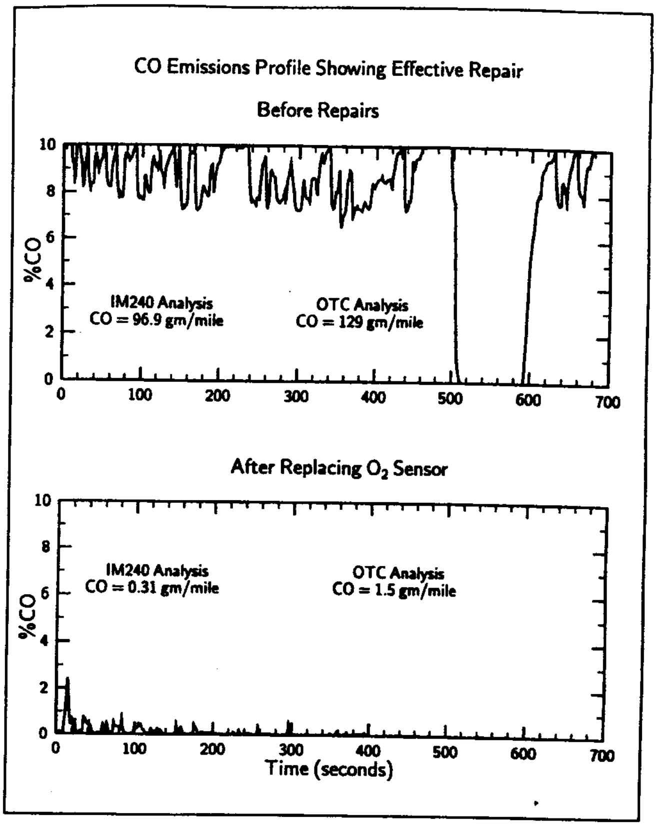

Figure 2. Second-by-second %CO emissions traces before (a) and after (b) successful repair of a 1988 Mercedes 190E 2.6L.

Plots of the second by second on-road emissions data for CO_2, CO, hexane, and O_2 were produced for the on-road studies of each vehicle measured. The X axis represented the time units in seconds. Each Y axis represented the measured concentration of a tail-pipe emission. For a given test run, the four plots could be overlaid with the same X axis. This allowed us to see at a given instant the emissions level of each gas. The second by second emission traces proved to be good predictors of repair need as well as repair effectiveness.

After acquiring the portable analyzers, one of the early candidates for repair based on the remote sensing measurement was a 1971 Mercury Cougar with a 400-cubic inch displacement V8 engine. The estimated CO mass emissions were over 100 grams per mile; however, on looking at the second-by-second emissions traces, it was determined that we should reject this vehicle for repairs because only the idle emissions were high. Every period of idle and low speed operation showed very high CO readings. Once the vehicle was at speed, the emissions dropped to low values. We were subsequently informed that this vehicle had recently had the engine overhauled and the idle emissions had been intentionally set high during the break-in period. Two other vehicles were rejected at this point because the portable analyzer demonstrated that while their emissions were high when passing the remote sensor at slow speeds, their on-road emissions were not excessive for their age. The intent of the program was to repair high on-road emitters, i.e., vehicles with high driving mode (as well as idle) emissions.

Two examples of second-by-second emissions data before and after repairs are shown in Figures 1 and 2. Figure 1a shows the first test of the %CO emissions from a 1980 Chevrolet Citation 2.8L (with close to 200,000 miles on the odometer). Figure 1b shows the %CO trace after a carburetor overhaul and minor tuneup adjustments. After the first repair the vehicle's emissions were reduced somewhat—an 18% reduction according to the portable analyzer from 68 to 56 grams/mile, and a 30% reduction according to IM240 from 96 to 68 grams per mile. However, we deemed this repair an inadequate reduction in the vehicle's CO emissions and so continued to look for other problems. After further carburetor adjustments and a new catalytic converter, the vehicle had noticeably lower %CO emissions as seen in Figure 1c.

Figure 2a shows the emissions trace of a 1988 Mercedes 190E 2.6L with remarkably high emissions for its age and odometer reading (45,000 miles). The y axis was limited to 10% CO in order to keep all vehicle traces on the same scale for easier intercomparison. Diagnosis quickly determined that the oxygen sensor (one of the key data inputs to the car's computer) had failed. The onboard diagnostics had not detected this failure and so the "Check Engine" light had not come on. After the oxygen sensor replacement, the %CO trace can be seen in Figure 2b, leaving no doubt that this emissions problem had been solved.

Five vehicles identified by means of remote sensing were tested using portable emissions analyzers before and after repairs. A comparison of the two methods for the seven vehicles that received IM240 and portable four-gas analyses in separate locations is shown in Figures 3 and 4. The slopes are higher than for the one vehicle which was measured while on the dynamometer, but the important point is the good linear correlations along with the small intercepts seen, which show little inherent bias in the comparison. This is noteworthy for the HC, analysis since some concern has been expressed regarding the ability of NDIR concentration analyzers to accurately reflect mass emissions measured with a flame ionization detector.[9] The correlation for mass emissions of CO ($r^2 = 0.87$) is better than the correlation obtained by the U.S. EPA for two IM240 readings on the same vehicle ($r^2 = 0.66$) and nearly as good for HC ($r^2 = 0.76$ versus $r^2 = 0.82$).[10] An important feature to notice in both Figures 3 and 4 is the fairly tight cluster of triangle data points (with one exception) near the origin. This indicates that IM240 and portable analyzers are equally able to distinguish low emitting vehicles from high emitters and thus gauge repair effectiveness, and that observed on-road reductions are reasonably proportional to observed IM240 reductions.

DISCUSSION

As a diagnostic tool, the portable analyzers enabled us to see the conditions under which high emissions were

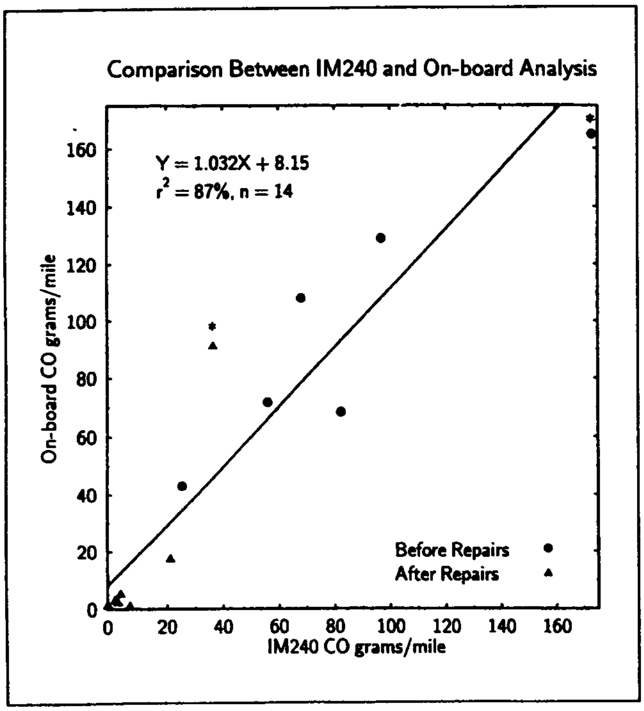

Figure 3. Correlation of portable analyzer %CO converted to grams per mile with IM240 grams per mile. The data points with the asterisk are from a tampered 1973 Jeep. The data points after repairs are shown as triangles and those before repair as circles.

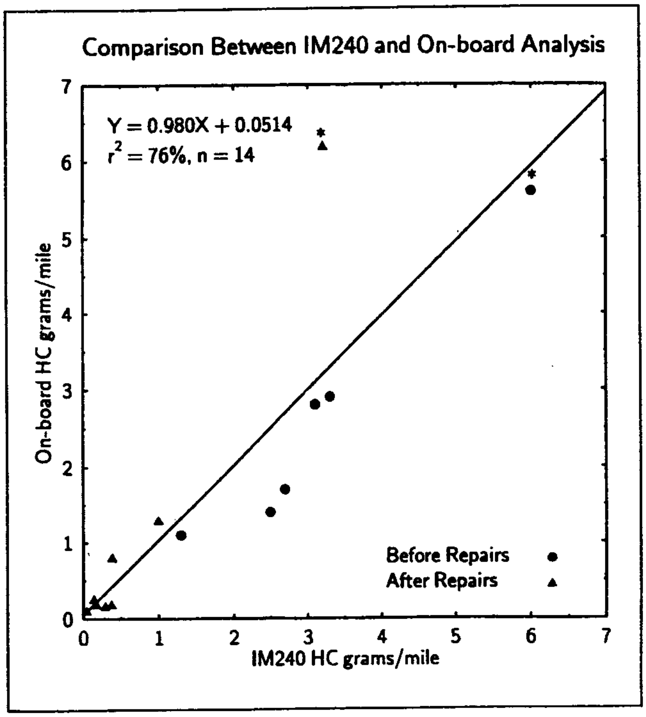

Figure 4. Correlation of portable analyzer ppm hexane converted to grams per mile with IM240 grams per mile. The data points with the asterisk are from a tampered 1973 Jeep. The data points after repairs are shown as triangles and those before repair as circles.

observed. To decide whether repairs were needed and in what driving mode the highest emissions occurred required little in the way of standardized procedures, except to ensure that the vehicle and sensors were fully warmed up before taking the drive. To evaluate how predictive of the IM240 emissions levels our test could be, we adhered to a more rigid protocol than would be necessary in normal field use.

Being able to predict successful repair of loaded mode emissions problems will become increasingly important with the introduction of IM240 (or other loaded mode) testing in many areas. In those areas, mechanics faced with an emissions repair will start with an IM240 test result, and the factor by which it needs to be reduced. They can then use portable analyzers and their own driving loops to establish a basis for comparing their initial data collection to the IM240 benchmark. Linear correlation between the IM240 and an on-road test, as seen in Figures 3 and 4, is more important than a slope of one, since proportional improvements can be observed from each kind of test. In fact, the repair shop would not even need to calibrate its on-road analyzer as long as the calibration did not change while an individual vehicle was being repaired. The evidence with our analyzers suggests that such calibration changes are not observed.

The poorer correlation between the on-road data (taken usually a day or two before and after the IM240 readings) compared to the data taken while the Nissan was on the dynamometer may be partially explained by the following observations. Large IM240 test-to-test variations on the same vehicle have been observed and become more pronounced as vehicle emissions increase.[10,11] The on-road data include many points from high emitters. The driving cycle for the 4-gas and the IM240 were the same for the Nissan, and any test to test IM240 differences caused by vehicle changes would also be picked up by the 4-gas analyzer. The Nissan analysis uses the measured fuel economy (about 33 mpg), not the CAFE assumption, which would have been 26 mpg for this vehicle. This factor alone would give rise to an expected slope of 0.79. The above observations may account for the improved precision with the Nissan, but unless there were calibration problems on the day of the side-by-side test, we cannot account for the slope differences other than to suggest that there were differences in the drive cycles between a true IM240 and the fixed on-road driving loop. Under the conditions of the Nissan study, the expected factor of two difference between NDIR hexane equivalency and flame ionization total carbon measurements was observed.[9]

A fixed driving loop which consists of all of the various vehicle operating conditions of the IM240 should maintain a fixed percentage difference between the mass emissions predicted using concentration data and IM240 within the errors introduced by vehicle variability. The most important difference between IM240 and the driving loops we used was the greater amount of idle emissions that were incorporated (by stop signs and traffic lights) into the portable analyzer data. Not knowing the average fuel economy produces an error that would remain fairly constant for a given vehicle. To the extent that fuel economy does not differ greatly upon repair, any consistent estimate of fuel economy could be used by a mechanic to estimate IM240 repair reduction fraction.

IM240 modal failures are vehicles with transient episodes of highly elevated emissions for short durations of the test cycle. Even though they are low-emitting for most of the test cycle, these vehicles can typically have average CO emissions in the 15 to 30 gram/mile range. Because a concentration analyzer is not sensitive to exhaust volume, a portable analyzer may under- or over-predict the emissions from such a vehicle, depending on the exhaust volume flow rate at the time of the high emissions. Studies have shown that it is uncertain whether these vehicles will be successfully diagnosed and repaired.[12] Most of the vehicles that were used in our repair program had emissions component problems which caused elevated emissions throughout the driving cycle. However, a consistent modal type failure should show up in the second-by-second traces during a test drive using a portable analyzer, provided the drive cycle contains all IM240 modal components.

CONCLUSIONS

The procedure described is a means to obtain loaded mode test results with inexpensive equipment that can also serve as a useful stand-alone emissions bench and analytical tool. The use of a portable analyzer, with proper data presentation, can make the difference between a technician who installs a new catalytic converter as a quick but temporary fix to get a vehicle to pass the test, and one who feels encouraged to locate and correct a component failure and thus produce a longer-term benefit. The portable analyzer takes up little garage space and is fast to set up and operate. Presently, the major drawback involves the need to use a portable computer in addition to the analyzer. This increases the number of steps necessary to extract the information from the analyzer and convert it into a more useful form, whether it is a visual, second-by-second emissions trace, or mass emissions in grams per mile. Current versions of the instruments do not have adequate data storage capabilities or the built-in ability to manipulate data, but this is changing with the growing interest in mass emissions diagnosis and repair.[13]

ACKNOWLEDGMENTS

The assistance of the City and County of Denver, Department of Health and Hospitals, Air Quality/Environmental Protection Division, the Administration and staff of the University of Denver and the Staff of the Remote Sensing Institute is greatly appreciated. The National Center for Vehicle

Emissions Control and Safety, as well as providing IM240 testing, proved to be a valuable resource for vehicle repair and advice. MPSI, who supplied the PGA 9000, and OTC, who supplied their Model 3400, enabled us to experiment with new tools which we believe will be vital to the repair industry for diagnosing and repairing on-road emissions problems.

REFERENCES

1. Denver Ordinance #330, December, 1990.
2. Bishop, G.A.; Starkey, J.R.; Ihlenfeldt, A.; Williams, W.J.; Stedman, D.H. "IR long-path photometry, a remote sensing tool for automobile emissions," *Anal. Chem.*, 1989, 61, 671A.
3. Lawson, D.R.; Groblicki, P.J.; Stedman, D.H.; Bishop, G.A.; Guenther, P.L. "Emissions from in-use motor vehicles in Los Angeles: a pilot study of remote sensing and the inspection and maintenance program," *J. Air Waste Manage. Assoc.* 1990, 40, 1096.
4. Ashbaugh, L.L.; Lawson, D.R.; Bishop, G.A.; Guenther, P.L.; Stedman, D.H.; Stephens, R.D.; Groblicki, P.J.; Parikh, J.S.; Johnson, B.J.; Huang, S.C. "On-road remote sensing of carbon monoxide and hydrocarbon emissions during several vehicle operating conditions," Paper presented at AWMA/EPA Conference on "PM_{10} Standards and Nontraditional Particulate Source Controls," Phoenix, AZ, Jan. 1992.
5. Bishop, G.A.; Stedman, D.H.; Peterson, J.E.; Hosick, T.J.; Guenther, P.L. "A cost-effectiveness study of carbon monoxide emissions reduction utilizing remote sensing," *J. Air Waste Manage. Assoc.* 1993, 43, 978.
6. Stedman, D.H.; Bishop, G.A.; Beaton, S.P.; Peterson, J.E.; Guenther, P.L.; McVey, I.F.; Zhang, Y. "On-road remote sensing of CO and HC emissions in California," Final Report, Contract No. A032-093, California Air Resources Board Feb. 1994.
7. Austin, T.C. "An evaluation of loaded mode I/M testing at service stations," report prepared by Sierra Research, Inc. for the State of California Bureau of Automotive Repair, Report No. SR88-12-02.
8. Stedman, Donald H.; Bishop, Gary A. "Evaluation of a remote sensor for mobile source CO emissions," prepared for the USEPA project # CR-815778-01-0, USEPA document EPA/600/4-90/032, January 1991.
9. Stephens, R.D.; Mulawa, P.A.; Giles, M.T.; Kennedy, K.G.; Groblicki, P.J.; Cadle, S.H.; Duncan, J.W.; Knapp, K.T. "An experimental evaluation of remote sensing based hydrocarbon measurements: a comparison to FID measurements," Proceedings of the Fourth CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, CA, March 16-18, 1994.
10. Calculated from data found in United States General Accounting Office. "Air pollution: unresolved issues may hamper success of EPA's proposed emissions program," GAO/RCED-92-288 (1992).
11. Bishop, G.A.; Stedman, D.H. "Remote sensing and vehicle variability," Proceedings of the Fourth CRC-APRAC On-Road Vehicle Emissions Workshop, San Diego, CA, March 16-18, 1994.
12. Lawson, D.R. "The costs of 'M' in I/M: reflections on inspection/maintenance programs," *J. Air Waste Manage. Assoc.* 1995, 45, 465.
13. Personal communication, Jon Nordman, OTC, December 14, 1994.

About the Authors

Paul Guenther (corresponding author) received his Master of Science degree from the Department of Chemistry at the University of Denver, 2101 East Wesley Ave., Denver, CO 80208, for developing the hydrocarbon channel for the remote sensor for vehicle emissions. Donald Stedman, Brainerd Phillipson Professor of Chemistry, is a co-inventor of the remote sensor for vehicle emissions. Jon Lesko is a Research Engineer working at the Denver Research Institute, Engineering Sciences Laboratory, Denver, CO.