FINAL REPORT

An Investigation of Remote Sensing Devices for Chemical Characterization of Motor Vehicle Exhaust

By

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ABSTRACT

The Air Pollution Prevention and Control Division (APPCD) of EPA's National Risk Management Research Laboratory, located in Research Triangle Park (RTP), NC, has conducted a series of tests to (1) evaluate the accuracy and precision of two different remote sensing devices (RSDs) for measuring carbon monoxide (CO), hydrocarbons (HCs), and nitric oxide (NO), and (2) evaluate the capabilities of three RSDs for characterizing fleet emissions of NO. This report summarizes the results of these tests and lays the groundwork for analysis efforts that will be the basis for future articles.

"Puff" tests were conducted in which bursts of *simulated* motor vehicle exhaust were repeatedly measured by the RSDs. The accuracy and precision of data from these measurements, which show a generally linear response over a range of concentrations, were in the order CO > HC > NO. Subsequently, three vehicles were driven at constant speed on a dynamometer and on a test track. The average emissions data measured by three RSDs at the track, when compared to the dynamometer emissions data (which were used as the "standard"), in general, showed just the opposite result; i.e., NO > HC >CO. However, the track data show a considerable amount of variation. Whether or not this was caused by the conditions at the site (e.g., only a slight grade, which made maintaining constant vehicle speed difficult) or some other variable is a question for possible future research.

The three RSDs were also tested for several hours on a freeway ramp in southwest Raleigh, NC. Considerable differences in readings for each individual vehicle by the three RSDs were noted. However, when the range of all emissions measurements for each RSD was grouped into intervals, the distributions of the data were very similar. This supports the conclusion that if enough data are collected, they should adequately indicate fleet emissions at a particular location.

ACKNOWLEDGMENTS

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LIST OF ACRONYMS

APPCD	Air Pollution Prevention and Control Division
FEAT	Fuel Efficiency Automobile Test
HCs	Hydrocarbons
I/M	Inspection and Maintenance
IR	Infrared
NCDEHNR	North Carolina Department of the Environment, Health, and Natural Resources
RSD	Remote Sensing Device
RTP	Research Triangle Park (North Carolina)
RSTi	Remote Sensing Technologies, Inc.
UV	Ultraviolet

INTRODUCTION

Remote sensing of automobile emissions is a technique developed in the late1980s. The remote sensing device (RSD) uses infrared (IR) and, in some cases, ultraviolet (UV) spectroscopy to measure the concentrations of pollutants in exhaust emissions as the vehicle passes a sensor on the roadway. RSDs have been used to develop a profile of the emission characteristics of the overall fleet of motor vehicles in metropolitan areas and/or to identify those vehicles known as "super emitters," which are responsible for much of automotive emissions.

The Air Pollution Prevention and Control Division (APPCD) of EPA's National Risk Management Research Laboratory, located in Research Triangle Park (RTP), NC, has conducted a series of tests to (1) evaluate the accuracy and precision of two different RSDs for measuring carbon monoxide (CO), hydrocarbons (HCs), and nitric oxide (NO), and (2) evaluate the capabilities of RSDs for characterizing fleet emissions of NO. NO measurements are based on a newer technology than that for measuring CO and HCs.

This report summarizes the results of these tests and lays the groundwork for analysis efforts that will be the basis for future articles.

BACKGROUND

Remote sensing enables the exhaust emissions of a motor vehicle to be measured as the vehicle passes by on the road. With this technique, which was developed in the late 1980s, IR spectroscopy, or a combination of IR and UV spectroscopies, is used to measure concentrations of carbon dioxide (CO_2), CO, HCs, and NO. A schematic of a typical RSD system appears in Figure 1. In addition to the source and detector, remote sensors may be equipped with meteorological stations and speed/acceleration systems which are important in interpreting exhaust measurements by the RSD.

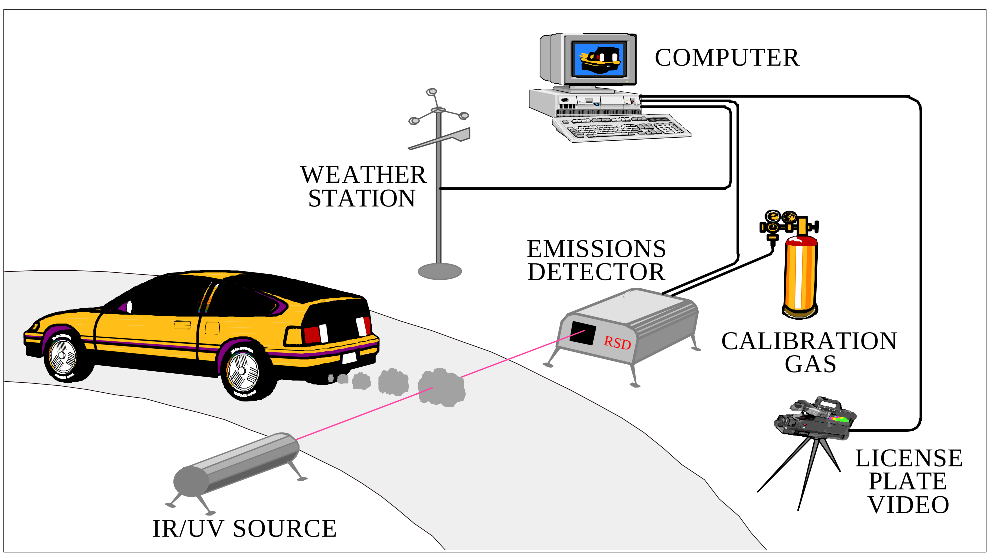

Figure 1. Components of the remote sensing device system.

The RSD technology is designed to measure CO, HC, and NO exhaust emissions of many thousands of vehicles per day and provides a practical approach for routinely characterizing on-road vehicle emissions. As such, remote sensing has several potential uses: determining fleet average emissions for inventory purposes,[1,2] characterizing fleet emissions distributions to evaluate vehicle inspection and maintenance (I/M) programs,[3] and to compare with other fleets for bench marking purposes.[4] EPA has issued detailed guidance on the use of RSDs in I/M programs.[5,6]

Previous remote sensing studies have indicated that most of the measured on-road emissions (over 50%) come from a disproportionately small percentage of the vehicles (approximately 10%).[7,8] This has been shown to be true for CO, HCs, and most recently for NO.[9] Since the remote sensing signal can be integrated with a video image of the license plate of the passing vehicle, RSDs can also be used to relate emissions data to the characteristics of specific classes of vehicles and, in some cases, identify high emitters.[10] With these potential applications, several states are considering adopting remote sensing as a supplement to their air quality improvement programs.[11]

Note that steady-state conditions do not represent vehicle emissions under transient operation where the highest emissions occur (e.g., during cold engine starts or rapid accelerations resulting in fuel enrichment). Thus, RSD results may in some cases over- or under-predict emissions. Despite these potential errors, RSDs, properly used, are very useful tools.

Calibration of the instrument and the calculation of exhaust constituent concentrations will be discussed briefly. The RSD functions much like a bench top spectrophotometer except that it has been adapted for the roadway. Each of the principal species of vehicle exhaust can be identified by its characteristic IR or UV spectrum. For example, in the RSD-1000 unit produced by Remote Sensing Technologies, Inc. (RSTi), absorption peaks produced by CO, HCs, and CO_2 in the exhaust plume are isolated by separate detectors focused at 4.6, 3.4, and 4.3 µm in the IR region, respectively. Donald Stedman's group at the University of Denver determined that using the absorption peak at 227 nm in the UV spectral region would avoid the interference from exhaust water vapor in the IR spectrum.[7] RSTi selected this approach for their NO channel. A reference table of measured absorption intensity at various constituent concentrations is created which enables the concentrations of constituents in vehicle exhaust plumes to be determined. If the width of the exhaust plume in the sensor beam (i.e., the path length) were known, concentrations of sample constituents could be calculated directly. But the path length of the plume is not known. Furthermore, the path length changes as the plume disperses and dilutes (Figure 2). By using the reference table values without correcting for the plume path length dynamics, incorrect concentrations would be produced because we would include the path length of the sample chamber in the calculations.

The inability to determine the path length of exhaust plumes is addressed by measuring the <u>relative</u> plume concentrations of exhaust constituents, not the <u>absolute</u> plume concentrations. Although the path length of the plume is unknown, it is assumed to be the same for all detectors at any given instant in time. Since the relative concentration at each instant in time is a function of concentration and path length, by dividing the concentration of one gas by another at each instant in time, the path length is removed from the equation. The slope of the relative concentrations as the

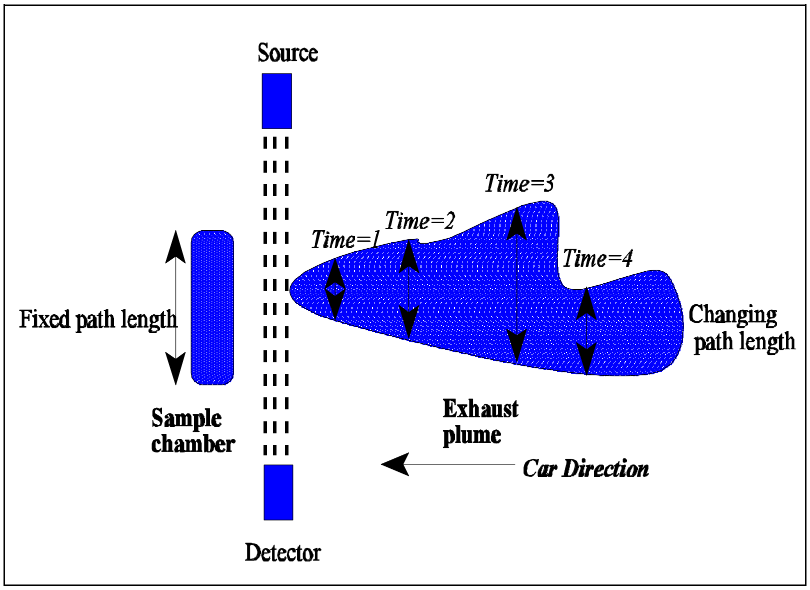

Figure 2. Path length dynamics.

plume disperses and dilutes provides the ratio of two gases (Figure 3).

The RSD determines the concentrations of CO, HCs, and NO in the tailpipes of passing vehicles by measuring the ratios of these gases to CO_2 in the exhaust plumes and by employing knowledge of the stoichiometry of gasoline combustion. For example, for the RSD-1000, the effective tailpipe concentrations of CO, HCs, NO, and CO_2 are computed through the combustion equations by assuming an empirical fuel formula and an ideal air/fuel ratio.[12,13] Since ambient CO_2 levels can be significant (350 ppmv or 0.035%)[14], a field calibration is conducted using a known gas mixture to remove the effects of ambient CO_2. During field calibration, a table of absorption versus concentration is constructed using CO as the reference in this case since ambient CO levels are low (0.1 ppmv).[15] Absorption and concentration are mathematically related by a polynomial equation typically of third or fourth order. New coefficients are derived for the terms in each constituent's polynomial equation, with the exception of CO, each time the RSD-1000 is field calibrated. The equation for CO remains unchanged since CO is used as the reference.

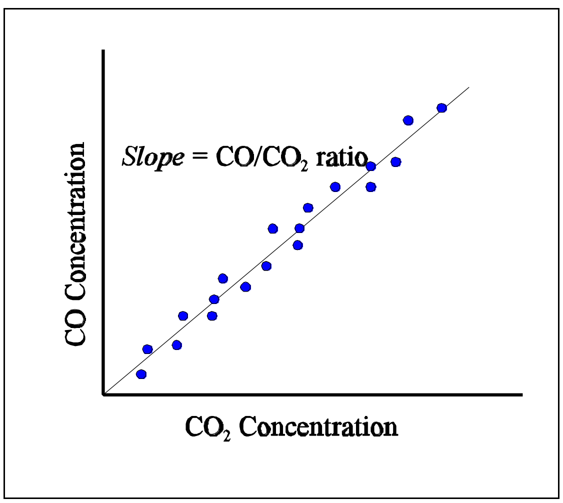

Figure 3. Plotting the relative concentrations provides the ratio.

Because the shape and contents of an exhaust plume from a motor vehicle are affected by a number of variables [e.g., the rate of acceleration, the speed, the location of the tailpipe (rear vs. side), the condition of the engine and its emission control system], and because remote sensing is a relatively new technology, there are concerns about the accuracy and precision of RSD measurements. For this reason, a series of laboratory and field experiments were conducted to evaluate the performance of several RSDs. These experiments are described below, after which summaries of the experimental data are presented. Note that detailed analyses of the data are not included in this report; these will be the objectives of subsequent efforts.

EXPERIMENTAL

Summary -- A series of six experiments using RSDs was performed:

(1) "Puff" tests in which *simulated* motor vehicle exhaust was repeatedly measured by an RSTi RSD-1000 using five certified gases representing a range of concentrations of CO_2, CO, propane (C_3H_8), and NO in a nitrogen matrix;*

(2) Puff tests in which *simulated* motor vehicle exhaust was repeatedly measured by a Hughes Environmental Systems, Inc. Smog Dog™ 3 using five certified gases in a manner similar to the tests with the RSD-1000;

(3) Puff tests in which *simulated* motor vehicle exhaust was repeatedly measured by three different RSDs [the RSD-1000 and Smog Dog™ 3 devices used previously, as well as a University of Denver Fuel Efficiency Automobile Test (FEAT) #3008 device] using three certified gases, each containing, in a nitrogen matrix, the same percentages of CO_2, CO, and C_3H_8, but a different percentage of NO;

(4) Dynamometer tests in which the actual exhaust of each of three different vehicles (a Dodge Minivan, Ford F-150 Pickup Truck, and Ford Mustang II) was measured by laboratory equipment while the vehicles were "driven" at constant speed;

(5) Track tests in which the actual exhaust plumes of the three vehicles tested on the dynamometer were repeatedly measured by three different RSDs (used previously in puff tests) as the vehicles passed the devices at a constant speed; and

(6) Road tests in which the actual exhaust plumes of vehicles were measured by the three different RSDs (used previously in puff tests) as the vehicles passed the devices at a freeway entrance ramp.

* These puff tests were supplemented by track tests in which the actual exhaust plume of an instrumented vehicle (IV) was repeatedly measured by the RSD-1000 as the IV passed the device. See Appendix A.

Experiment 1: RSD-1000 "Puff" Tests

This experiment involved repeated measurements of five known mixtures of simulated (dry) motor vehicle exhaust. Each of the mixtures was puffed into the path of the sensor 100 times with the system calibrated using one of three available calibration gas mixtures (only those mixtures containing NO could be used to fully calibrate the instrument). Table 1 lists the gases that were puffed, which include the three used to calibrate the sensor. Gas components at these relative levels represent tailpipe concentrations ranging from 1 to 9% CO, 300 to 4100 ppm HCs as propane, and 1500 to 3600 ppm NO. Gases used in the experiment were Scott Master Certified® (±2%) gases.

Because the calibration procedure is a possible source of error, the experiment was designed so that separate variance components for calibration error and gas puff error could be estimated. The 100 puff measurements were obtained in four groups of 25, each group after a fresh calibration.

Table 1. Gas Mixtures Used to Calibrate and Puff in the RSD-1000 Precision/Accuracy Tests

Gas Mixture	CO, %	HC, ppm	NO, ppm	CO_2, %	CO/CO_2 ratio	HC/CO_2 ratio	NO/CO_2 ratio
1 (Calibration 1)	3.05	3940	3590	12.90	0.236	0.030	0.028
2	4.00	1200	0	12.00	0.333	0.010	0
3 (Calibration 3)	6.44	6350	1500	10.54	0.611	0.060	0.014
4 (Calibration 2)	6.03	2795	1997.5	5.98	1.008	0.046	0.033
5	1.00	300	0	14.00	0.071	0.002	0

The objective of this experiment was not only to determine the accuracy and precision of the RSD-1000 over a typical range of operation (0 - 1.0) for CO/CO_2 ratio, (0 - 0.06) for HC/CO_2 ratio, (0 -0.04) for NO/CO_2 ratio, but to determine whether the instrument's response was linear. This was accomplished by calibrating with gas mixtures that spanned the observable range of automobile exhaust. The concentrations of components in each of the mixtures, except gas #4, were selected using the dry gas combustion equation and, therefore, reflect proportions observed in dry tailpipe exhaust. Gas #4 is the manufacturer's recommended calibration gas.

Experiment 2: Smog Dog™ 3 "Puff" Tests

This experiment involved repeated measurements of five known mixtures of simulated (dry) motor vehicle exhaust, and was, with a few exceptions, identical to experiment 1 with the RSD-1000 device. Again, each of the mixtures was puffed into the path of the sensor 100 times with the system calibrated using one of three available calibration gas mixtures. Table 2 lists the gases that were puffed, which include the three used to calibrate the sensor. Gas #4 is the manufacturer's recommended calibration gas. Note that gas #1 has almost the same composition as gas #1 in experiment 1, while gases #2, 3, and 5 are identical to those used in that experiment with the RSD-1000 device.

Table 2. Gas Mixtures Used to Calibrate and Puff in the Smog Dog™ 3 Precision/Accuracy Tests

Gas Mixture	CO, %	HC, ppm	NO, ppm	CO_2, %	CO/CO_2 ratio	HC/CO_2 ratio	NO/CO_2 ratio
1 (Calibration 1)	3.01	4297	4137	13.30	0.226	0.032	0.031
2	4.00	1200	0	12.00	0.333	0.010	0
3 (Calibration 3)	6.44	6350	1500	10.54	0.611	0.060	0.014
4 (Calibration 2)	15.11	19900	3820	15.01	1.007	0.133	0.025
5	1.00	300	0	14.00	0.071	0.002	0

Experiment 3: "Puff" Tests with Three RSDs

This experiment, like experiments 1 and 2, involved repeated measurements of known mixtures of simulated (dry) motor vehicle exhaust. However, this experiment was focused on assessing the accuracy and precision of *NO measurements,* and involved *three different RSDs*. The RSDs tested were the RSD-1000 and Smog Dog™ 3 devices used previously, as well as a University of Denver FEAT #3008 device. Each of three gas mixtures was puffed into the path of each sensor 100 times; each RSD system was calibrated using the same single calibration gas mixture. Table 3 lists the gases that were puffed, which basically differed only in their concentration of NO, and the gas used to calibrate the three different devices.

Table 3. Gas Mixtures Used to Calibrate and Puff in the RSD NO Precision/Accuracy Tests

Gas Mixture	CO_2, %	CO, %	HC, ppm	NO, ppm	NO/CO_2 ratio
1	15.01	0.300	500.0	500.	0.0033
2	14.99	0.300	502.6	999.	0.0067
3	15.00	0.299	502.0	1496.	0.0100
4 (Calibration Gas)	13.30	3.01	4297	4137	0.0311

Note: Prior to the testing, the RSD manufacturers all agreed that gas mixture # 4, which was readily available, could be used for calibrating their instruments in these tests. Although somewhat different from what they would recommend for *fleet characterization testing* under road conditions, the gas was similar enough to be adequate for these tests.

Experiment 4: Dynamometer Tests on Three Vehicles

This experiment involved measurements by laboratory equipment of the actual exhaust of each of the three vehicles used in experiment 5. Each vehicle was "driven" at constant speed (45 mph*) on a dynamometer at EPA's facilities in Research Triangle Park, NC. The results of this test established the "standard" by which the track test emission measurements using the RSDs would be evaluated.

Each vehicle was tested three times for 10 minutes (30 minutes total). Emissions from the vehicles were diluted and analyzed on a second-by-second basis; "bag" samples were also taken and analyzed to obtain a mean concentration value for the entire test. However, because some of the NO in the bag samples was converted to NO_2, the second-by-second data was adjusted and used as the "standard." The adjustment used the "middle" 8 minutes of test data (the first and tenth minutes of data were dropped to eliminate some of the effects of start-up and driver variability).

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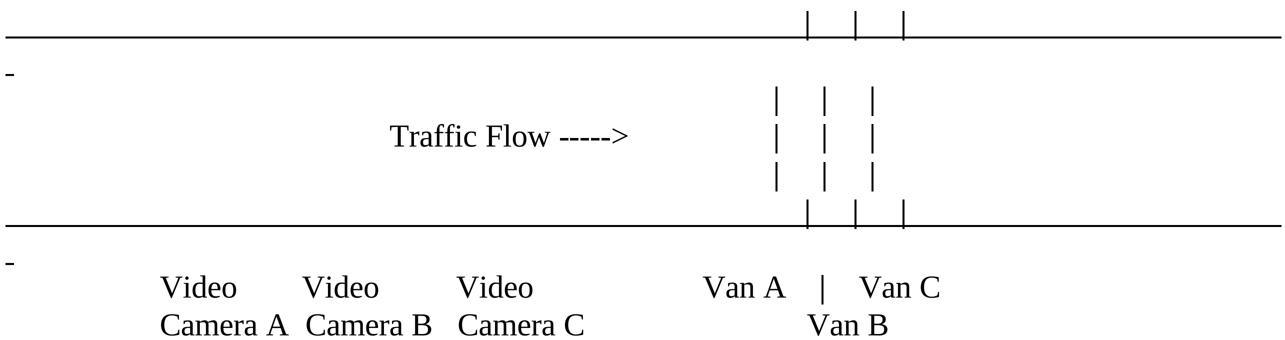
* Readers more familiar with the metric system may use the following factors to convert from nonmetric units in this report: 1 ft = 30.48 cm; 1 in. = 2.54 cm; 1 mi = 1.61 km; and 1 mph = 1.61 km/h.

Experiment 5: Track Tests with Three RSDs

This experiment involved measurements of CO, HC, NO, and CO_2 concentrations in the automotive tailpipe exhaust of three different vehicles driven repeatedly past several different RSDs. The RSDs used were the three devices tested in experiment 3, as well as a Smog Dog™ device owned and operated by the North Carolina Department of Environment, Health, and Natural Resources (NCDEHNR). Since the NCDEHNR's device did not measure NO, which, like experiment 3, was emphasized in this testing, no results for that device are included here.

The tests were conducted on the NC Highway Patrol's 1.13-mile oval test track in Raleigh, NC. To ensure that the vehicles passed under constant-applied throttle, the RSDs were positioned near the crest of a long and gradual 0.3% uphill slope. The equipment vans which supported the RSDs were positioned beside the track so that the beams which emanated from the devices were as close together as possible (Figure 4). Specifically, the distance between the FEAT #3008 and Smog Dog™ 3 was about 9 ft., 4 in. (the NCDEHNR device was located between them), while the distance between the Smog Dog™ 3 and the RSD-1000 beams was about 3 ft., 7 in. In addition, the IR/UV beams were approximately the same height (16-19 in.) above and parallel to the road surface.



Note: A = FEAT #3008; B =Smog Dog™ 3; C = RSD-1000

Figure 4. Relative location of RSDs at NC Highway Patrol's test track in Raleigh, NC.

The vehicles made approximately 100 laps around the track (in four groups of about 25), passing through all of the beams during each lap. The participating devices were calibrated with puff gases prior to testing and were recalibrated after each group of 25 laps. With the exception of the RSD-1000, the calibration puff gases used were those recommended by the manufacturers prior to the testing described in experiment 3. The actual gases used are described in Table 4.

Table 4. Gas Mixtures Used to Calibrate the RSDs in Experiments 5 and 6

Cal Gas for:	CO, %	HC, ppm	NO, ppm	CO_2, %	CO/CO_2 ratio	HC/CO_2 ratio	NO/CO_2 ratio
FEAT #3008	6.01	2005	1003	6.02	0.998	0.0333	0.0167
RSD-1000	3.01	4297	4137	13.01	0.231	0.0330	0.0318
Smog Dog™ 3	15.01	19900	3820	15.10	0.994	0.132	0.0253

Experiment 6: On-Road Testing with Three RSDs

This experiment involved measurements of CO, HC, NO, and CO_2 concentrations in the automotive tailpipe exhaust of moving vehicles on two freeway on-ramps in the RTP, NC, area. The RSDs used were the same four devices used in experiment 4. Again, of particular interest were the capabilities of the devices to accurately detect NO emissions, so the NCDEHNR data are not included here. The tests were conducted at two on-ramps to Interstate Highway 40 (I-40), one in southwest Raleigh (Wake County), the other in the southern part of Durham County. Unfortunately, the computer on board the RSD-1000 van failed early in the testing at the Durham County site, so all three devices can be compared only through data collected at the Raleigh site.

The equipment vans, which supported the RSDs, were positioned on the shoulder of the road in a manner similar to that shown in Figure 4. However, the order of the RSDs was different, as was the distance between the IR/UV beams. Specifically, the order was:

S Gorman St. Entrance to I-40 W in Raleigh, NC –
FEAT #3008, RSD-1000, and Smog Dog™ 3

NC-147 N Entrance to I-40 E in Durham County, NC --
Smog Dog™ 3, RSD-1000, and FEAT #3008

In this experiment, the beams were about 3 ft. apart. Again, the beams were approximately the same height (16-19 in.) above and parallel to the road surface.

RESULTS

Experiment 1

A summary of the RSD-1000 puff test results is shown in Tables 5a-5c. The Group number designates a series of puffs that were initiated after the device was calibrated; N indicates the number of puffs in each Group. The mean and standard deviation (Std Dev) are shown for each series of puffs.

<u>Gas Mix 1 as the Calibration Gas (Table 5a)</u> -- In this set of tests, the CO/CO_2 group mean values were best for the calibration gas. For higher concentrations of CO, the CO/CO_2 group mean values were underestimations of the expected values; e.g., those for Gas Mix 4 represented about a 15 % underestimation. For Gas Mix 5, which had a lower concentration of CO, the group mean values *overestimated* the expected value of CO/CO_2 by about 9 to 20 %. The precision of this series of tests was very good; the worst was for Gas Mix 5, but the standard deviations for these groups were less than 6 % of the means. For all the other gases, the standard deviations were less than 2 % of the means. A linear fit of all the CO/CO_2 group means gave an r^2 of 0.998.

The accuracy of the HC/CO_2 measurements (Table 5a) was better overall than those for CO/CO_2, but the precision was not quite as good. Although the group means, in general, were below the expected values, they were on occasion above; the largest difference was for one of the Gas Mix 2 groups, where the mean was about 11 % lower than the expected value. The standard deviations for the Gas Mix 5 groups ranged from about 12 to 21 % of the means, but this was for a gas containing a very low concentration of HCs (HC/CO_2 = 0.002143). For all the other gases, the standard deviations were less than 4 % of the means. A linear fit of all the HC/CO_2 group means gave an r^2 of 0.998.

Also in Table 5a, for Gas Mixes 1 (the calibration gas) and 3, which had similar expected NO/CO_2 values (0.027829 and 0.033403, respectively), the NO/CO_2 group means covered similar ranges, with values both higher and lower than the expected values. The maximum difference was less than 8 %. However, for Gas Mix 4, the group means were all higher than the expected value; they averaged about 13 % higher, with a maximum difference of about 21 %. This pattern was similar to the results for CO, where the higher concentration calibration gas gave an overestimation of a lower concentration gas. The precision for these measurements was worse overall than those for CO and HCs. The standard deviations for data groups of the three gas mixes containing NO ranged from about 9 to 21 % of the means. Despite this, a linear fit of all the group means gave an r^2 of 0.990.

Table 5a. Puff Test Results for the RSD-1000 Calibrated with Gas Mix 1

Gas Mix	Group	N	CO/CO_2 Ratio			HC/CO_2 Ratio			NO/CO_2 Ratio		
			Expected	Mean	Std Dev	Expected	Mean	Std Dev	Expected	Mean	Std Dev
1	1	25	0.236434	0.23629	0.002993	0.030543	0.030641	0.000635	0.027829	0.024753	0.003838
	2	25	0.236434	0.236484	0.003297	0.030543	0.030566	0.000518	0.027829	0.028684	0.002978
	3	25	0.236434	0.238174	0.003225	0.030543	0.030446	0.000586	0.027829	0.029632	0.00502
	4	25	0.236434	0.234844	0.002812	0.030543	0.030796	0.000384	0.027829	0.027366	0.002509
2	1	25	0.333333	0.318579	0.00281	0.0100	0.009466	0.000343	0	-0.00039	0.002742
	2	25	0.333333	0.316387	0.004042	0.0100	0.009996	0.000382	0	-0.00089	0.003109
	3	25	0.333333	0.316362	0.004797	0.0100	0.009516	0.000316	0	-0.00015	0.002769
	4	25	0.333333	0.314568	0.003557	0.0100	0.008921	0.000325	0	-0.00066	0.002128
3	1	25	0.611006	0.561189	0.006228	0.060247	0.059668	0.000933	0.014232	0.017194	0.003013
	2	25	0.611006	0.548256	0.007603	0.060247	0.057299	0.001331	0.014232	0.014286	0.003056
	3	25	0.611006	0.548804	0.010791	0.060247	0.05773	0.001591	0.014232	0.016596	0.002984
	4	25	0.611006	0.537615	0.008714	0.060247	0.058482	0.001146	0.014232	0.01621	0.003179
4	1	25	1.008361	0.860694	0.010364	0.046739	0.043349	0.001123	0.033403	0.03484	0.005286
	2	25	1.008361	0.851913	0.014053	0.046739	0.044791	0.001084	0.033403	0.035889	0.004349
	3	25	1.008361	0.842408	0.015118	0.046739	0.044944	0.001138	0.033403	0.034157	0.003938
	4	25	1.008361	0.853434	0.008759	0.046739	0.042296	0.001002	0.033403	0.032119	0.004446
5	1	25	0.071429	0.078752	0.001433	0.002143	0.00219	0.000386	0	0.000068	0.002365
	2	25	0.071429	0.077888	0.001605	0.002143	0.0021	0.000245	0	0.0001	0.002835
	3	25	0.071429	0.08543	0.004696	0.002143	0.002351	0.000491	0	-0.00036	0.002956
	4	25	0.071429	0.080662	0.00353	0.002143	0.002195	0.000327	0	0.00002	0.002307

Gas Mix 3 as the Calibration Gas (Table 5b) -- In this set of tests, the CO/CO_2 group mean values were best for the calibration gas. For higher concentrations of CO, the CO/CO_2 group mean values were underestimations of the expected values; i.e., those for Gas Mix 4 represented about a 5 to 7 % underestimation. For Gas Mixes 1, 2, and 5, which had a lower concentration of CO, the group mean values *overestimated* the expected value of CO/CO_2 by about 5 to 18 %. Again, this fits the pattern of the test results using Gas Mix 1 as the calibration gas. The precision of this series of tests was excellent; all of the standard deviations for the groups were less than 4 % of the means. A linear fit of all the CO/CO_2 group means gave an r^2 of 0.997.

As with the tests using Gas Mix 1 as the calibration gas, the accuracy of the HC/CO_2 measurements (Table 5b) was better overall than those for CO/CO_2. However, with the exception of the tests with Gas Mix 5, the precision was similar. The group means were above and below the expected values; the differences between group means and expected values for all the gas mixes were all less than 9 %. The standard deviations for the Gas Mix 5 groups ranged from about 12 to 19 % of the means, but this was for a gas containing a very low concentration of HCs (HC/CO_2 = 0.002143). For all the other gases, the standard deviations were less than 4 % of the means. A linear fit of all the HC/CO_2 group means gave an r^2 of 0.998.

The results for NO using Gas Mix 3 as the calibration gas (Table 5b) were inconsistent. The tests with Gas Mix 1 resulted in NO/CO_2 group means that were all underestimates of the expected values. Since the NO concentration in Gas Mix 3 was lower than that of Gas Mix 1, this appeared to fit the pattern seen with CO. However, the tests with Gas Mix 4, which had just a slightly higher concentration than that of Gas Mix 1, resulted in group means that were both higher and lower than the actual value. Even more surprising was the fact that the largest differences between the NO/CO_2 group means and the expected value occurred in tests with Gas Mix 3, *the calibration gas.* In these tests, the differences ranged from about -4 to +22 % of the expected value. Differences for Gas Mixes 1 and 4 were a maximum of -16 and -11 %, respectively. The precision of the data followed a similar pattern; the best was with Gas Mix 1 (14 to 17 % of the means), while the worst was with Gas Mix 3 (13 to 32 % of the means). Overall, the precision for these measurements was worse than those for CO and HCs. Despite this, a linear fit of all the group means gave an r^2 of 0.984; however, a cubic equation fit gave an r^2 of 0.991.

Table 5b. Puff Test Results for the RSD-1000 Calibrated with Gas Mix 3

Gas Mix	Group	N	CO/CO_2 Ratio			HC/CO_2 Ratio			NO/CO_2 Ratio		
			Expected	Mean	Std Dev	Expected	Mean	Std Dev	Expected	Mean	Std Dev
1	1	25	0.236434	0.266558	0.004823	0.030543	0.031405	0.000612	0.027829	0.024676	0.004077
	2	25	0.236434	0.259557	0.004666	0.030543	0.032384	0.000618	0.027829	0.026739	0.004163
	3	25	0.236434	0.260142	0.004075	0.030543	0.03152	0.000504	0.027829	0.026092	0.003579
	4	25	0.236434	0.257566	0.00409	0.030543	0.033049	0.000604	0.027829	0.023291	0.003534
2	1	25	0.333333	0.349382	0.005195	0.0100	0.010036	0.000229	0	0.000048	0.00256
	2	25	0.333333	0.357014	0.005693	0.0100	0.010415	0.000339	0	0.000199	0.002603
	3	25	0.333333	0.358065	0.006496	0.0100	0.010197	0.000211	0	-0.00031	0.002706
	4	25	0.333333	0.363864	0.00538	0.0100	0.010195	0.000356	0	-0.00103	0.002849
3	1	25	0.611006	0.612471	0.011556	0.060247	0.059904	0.001603	0.014232	0.01732	0.004539
	2	25	0.611006	0.61547	0.010182	0.060247	0.059317	0.001836	0.014232	0.015282	0.003417
	3	25	0.611006	0.611711	0.011846	0.060247	0.060423	0.001411	0.014232	0.013625	0.004295
	4	25	0.611006	0.610452	0.010404	0.060247	0.060686	0.001394	0.014232	0.015738	0.002056
4	1	25	1.008361	0.95066	0.012189	0.046739	0.04516	0.001013	0.033403	0.029663	0.004663
	2	25	1.008361	0.94411	0.011711	0.046739	0.04434	0.001108	0.033403	0.033336	0.004204
	3	25	1.008361	0.960901	0.027607	0.046739	0.045191	0.001256	0.033403	0.033483	0.007898
	4	25	1.008361	0.940967	0.017383	0.046739	0.045762	0.000925	0.033403	0.035135	0.004436
5	1	25	0.071429	0.084074	0.002469	0.002143	0.002165	0.00042	0	-0.00023	0.003241
	2	25	0.071429	0.082501	0.002027	0.002143	0.002155	0.000253	0	0.00087	0.003607
	3	25	0.071429	0.083149	0.002886	0.002143	0.002038	0.000277	0	0.000415	0.003684
	4	25	0.071429	0.080153	0.002969	0.002143	0.002011	0.000339	0	-0.00014	0.00447

Gas Mix 4 as the Calibration Gas (Table 5c) -- In this set of tests, the CO/CO_2 group mean values were best for the calibration gas. Gas Mix 4 had the highest concentration of CO, so, following the pattern of previous testing, the CO/CO_2 group mean values for tests with the remaining four gas mixes were overestimations of the expected values. The overestimation increased (as a %age of the true value) as the CO concentration decreased. For example, Gas Mix 3 gave means about 3 to 4 % above the expected value, while Gas Mix 5 gave means 28 to 32 % above the expected value. However, precision was good for all of the tests; the standard deviations for all the CO/CO_2 groups were 2 % or less, even for Gas Mix 5. As a result, a linear fit of all the group means gave an r^2 of 0.999.

As with the tests using Gas Mixes 1 and 3 as the calibration gases, the accuracy of the HC/CO_2 measurements (Table 6c) was better overall than those for CO/CO_2. However, the precision overall was not quite as good. The group means were above and below the expected values. The differences between group means and actual values for Gas Mixes 1- 4 were all less than 5 %; for Gas Mix 5, they ranged from 7 to 11 %. The standard deviations for the Gas Mix 5 groups ranged from about 7 to 10 % of the means; for all the other gases, the standard deviations were less than 5 % of the means. A linear fit of all the HC/CO_2 group means gave an r^2 of 0.999.

The results for NO using Gas Mix 4 as the calibration gas (Table 5c) were inconsistent. The tests with Gas Mix 1 resulted in NO/CO_2 group means that were all underestimates of the expected value. In fact, these tests showed the largest differences between the group means and the expected value (-5 to -24 %). The results with Gas Mixes 3 and 4 were similar, with group means above and below the expected values; for Gas Mix 3, they ranged from -7 to +8 % and for Gas Mix 4 (the calibration gas), from -5 to +8 %. The precision of the data was not particularly good, ranging from about 11 to 26 %. Despite this, a linear fit of all the group means gave an r^2 of 0.981; however, a cubic equation was required to give a fit comparable to those for the CO and HC data (an r^2 of 0.992).

In summary, it appears that when the RSD-1000 was calibrated with a mixture containing CO at a high ratio to CO_2, the measurement of gas mixtures containing CO at a lower ratio to CO_2 was increasingly overestimated, on average, by the device. The reverse was true when a low CO/CO_2 ratio mixture was used for calibration and a high ratio gas was puffed; in this case the higher ratio gases were underestimated. This pattern did not appear to hold for HCs and NO. This problem has reportedly been noted by the manufacturer and dealt with in more recent models of the device.

The accuracy of the RSD-1000 HC measurements was better overall than those for CO, while the accuracy of the NO measurements was not as good overall as those for CO and HCs. The precision of the measurements was best for CO, not quite as good for HCs, and worst for NO. However, the linear fit of the group means of all the data, *at its worst*, resulted in an r^2 of 0.981.

Table 5c. Puff Test Results for the RSD-1000 Calibrated with Gas Mix 4

Gas Mix	Group	N	CO/CO_2 Ratio			HC/CO_2 Ratio			NO/CO_2 Ratio		
			Expected	Mean	Std Dev	Expected	Mean	Std Dev	Expected	Mean	Std Dev
1	1	25	0.236434	0.26391	0.004664	0.030543	0.031738	0.000917	0.027829	0.026332	0.004403
	2	25	0.236434	0.265342	0.005236	0.030543	0.030525	0.000587	0.027829	0.025214	0.004449
	3	25	0.236434	0.262416	0.004273	0.030543	0.032	0.000753	0.027829	0.021273	0.003709
	4	25	0.236434	0.260852	0.00498	0.030543	0.031887	0.000473	0.027829	0.024172	0.003522
2	1	25	0.333333	0.361436	0.006292	0.0100	0.009847	0.00028	0	-0.00076	0.002032
	2	25	0.333333	0.355815	0.006486	0.0100	0.010265	0.000433	0	-0.00076	0.002369
	3	25	0.333333	0.347082	0.006802	0.0100	0.009732	0.000453	0	0.000348	0.004074
	4	25	0.333333	0.349268	0.006301	0.0100	0.009661	0.000367	0	-0.00013	0.003269
3	1	25	0.611006	0.635164	0.009284	0.060247	0.059549	0.001011	0.014232	0.01539	0.003743
	2	25	0.611006	0.630512	0.012866	0.060247	0.059909	0.000889	0.014232	0.013267	0.003467
	3	25	0.611006	0.636317	0.009167	0.060247	0.061169	0.001138	0.014232	0.013775	0.003625
	4	25	0.611006	0.634238	0.006539	0.060247	0.059488	0.001127	0.014232	0.014122	0.003576
4	1	25	1.008361	0.996811	0.011986	0.046739	0.046565	0.000692	0.033403	0.034958	0.00532
	2	25	1.008361	1.011076	0.012473	0.046739	0.046808	0.000975	0.033403	0.033314	0.003683
	3	25	1.008361	1.008984	0.012262	0.046739	0.046445	0.000944	0.033403	0.031805	0.006459
	4	25	1.008361	1.020835	0.012262	0.046739	0.04688	0.00121	0.033403	0.036079	0.00571
5	1	25	0.071429	0.093625	0.001868	0.002143	0.002358	0.000228	0	0.000167	0.002706
	2	25	0.071429	0.094111	0.001405	0.002143	0.002303	0.000258	0	-0.0003	0.002767
	3	25	0.071429	0.093876	0.001497	0.002143	0.002293	0.000199	0	0.000766	0.002413
	4	25	0.071429	0.091476	0.001354	0.002143	0.002335	0.000171	0	-0.00076	0.003151

Experiment 2

A summary of the Smog Dog™ 3 puff test results is shown in Tables 6a-6c. The Group number designates a series of puffs that were initiated after the device was calibrated, and N indicates the number of puffs in each Group. The means and standard deviations (Std Dev) of the CO/CO_2, HC/CO_2, and NO/CO_2 ratios are shown for each series of puffs.

<u>Gas Mix 1 as the Calibration Gas (Table 6a)</u> -- In this set of tests, the CO/CO_2 group means were fairly close to the expected value in all cases. The worst discrepancy was in the test with Gas Mix 4, where the group means ranged from about 4 to 11 % higher than the expected value. (Note that Gas Mix 4 had a higher concentration that Gas Mix 1, so the bias noted in experiment 1 with the RSD-1000 did not occur with this device.) The tests with the other gases gave group means higher and lower than the expected value, but the differences were all less than 5 % of the expected value. The precision was fairly good; the largest standard deviation for the Gas Mix 5 groups was about 5 % of the mean, while those for the remaining gas mixes were all less than 3 % of their means. A linear fit of the means gave an r^2 of 0.997.

On the other hand, the situation was much worse for the HC/CO_2 group means (Table 6a). The HC/CO_2 group means for Gas Mix 3 were about 13 to 15 % higher than expected value, while the group means for Gas Mix 4 were about *93 to 143 % higher* than the expected value. On the other hand, the HC/CO_2 group means for Gas Mix 3 were about 3 to 13 % lower than the expected value. The precision for the HC measurements was also not as good as that for CO. Although the standard deviations for data groups for Gas Mixes 1-3 ranged from about 2 to 6 % of their means, those for Gas Mix 4 ranged from about 7 to 11 %. The standard deviations for data group for Gas Mix 5 ranged from about 10 to 29 % of their means, but the concentration of HC in this gas mix was very low (less than 10 % of the HC concentration of Gas Mix 1). Despite this, a linear fit of the means gave an r^2 of 0.94; however, a second order polynomial fit gave an r^2 of 0.988.

The NO/CO_2 group means (Table 6a) were inconsistent. The group means for tests with the *calibration gas* (Gas Mix 1) were about 9 to 13 % higher than the expected value. For Gas Mixes 3 and 4, however, the NO/CO_2 group means were about 32 to 35 % and about 8 to 12 % *lower* than the expected values, respectively. The precision for the NO measurements was not quite as good as that for HCs. The standard deviations for Gas Mixes 1 and 4 ranged from about 4 to 9 % of the group means, while for Gas Mix 3, the standard deviations ranged from about 11 to 23 % of the means. Despite this, a linear fit of the means gave an r^2 of 0.965; however, a second order polynomial gave an r^2 of 0.993.

Table 6a. Puff Test Results for the Smog Dog™ 3 Calibrated with Gas Mix 1

Gas Mix	Group	N	CO/CO_2 Ratio			HC/CO_2 Ratio			NO/CO_2 Ratio		
			Expected	Mean	Std Dev	Expected	Mean	Std Dev	Expected	Mean	Std Dev
1	1	25	0.226316	0.227204	0.004275	0.032308	0.032768	0.000515	0.031105	0.033932	0.00134
	2	25	0.226316	0.230684	0.005077	0.032308	0.032268	0.000775	0.031105	0.034388	0.00318
	3	25	0.226316	0.224996	0.004013	0.032308	0.032628	0.000982	0.031105	0.033888	0.002901
	4	25	0.226316	0.230312	0.003112	0.032308	0.032352	0.000601	0.031105	0.035256	0.002472
2	1	25	0.333333	0.327344	0.005553	0.0100	0.010664	0.000673	0	-0.00224	0.000868
	2	25	0.333333	0.330488	0.004391	0.0100	0.010376	0.000296	0	-0.00254	0.001058
	3	25	0.333333	0.327304	0.00335	0.0100	0.010572	0.000349	0	-0.00309	0.000828
	4	25	0.333333	0.327652	0.004622	0.0100	0.010348	0.000318	0	-0.00276	0.001008
3	1	25	0.611006	0.622044	0.010288	0.060246	0.068392	0.002436	0.014232	0.009356	0.00135
	2	25	0.611006	0.602744	0.010624	0.060246	0.069304	0.003194	0.014232	0.009332	0.001046
	3	25	0.611006	0.616624	0.01389	0.060246	0.06862	0.002735	0.014232	0.009284	0.00211
	4	25	0.611006	0.617844	0.016115	0.060246	0.067832	0.002192	0.014232	0.009676	0.00180
4	1	25	1.006662	1.11258	0.025994	0.132578	0.25602	0.024482	0.02545	0.023472	0.001274
	2	25	1.006662	1.04726	0.031056	0.132578	0.267396	0.023786	0.02545	0.022324	0.001303
	3	25	1.006662	1.09566	0.018841	0.132578	0.322783	0.023619	0.02545	0.023268	0.001677
	4	25	1.006662	1.08156	0.017945	0.132578	0.284868	0.030145	0.02545	0.022796	0.001502
5	1	25	0.071429	0.074884	0.002148	0.002143	0.002068	0.000214	0	0.000328	0.001327
	2	25	0.071429	0.0725	0.003124	0.002143	0.001872	0.000786	0	0.000384	0.001562
	3	25	0.071429	0.070348	0.003543	0.002143	0.00194	0.000456	0	0.000116	0.002286
	4	25	0.071429	0.075188	0.003613	0.002143	0.00228	0.000665	0	-0.00014	0.001783

Gas Mix 3 as the Calibration Gas (Table 6b) -- In this set of tests, the CO/CO_2 group means were fairly close to the expected value in all cases; the maximum difference was a maximum of 6 %. The precision was also good; all standard deviations were less than 5 % of their means. Not surprisingly, a linear fit of the means gave an excellent r^2 of 0.9995.

For gas mixes with HC concentrations lower than that of Gas Mix 3, the HC/CO_2 group means were all underestimates of the expected value. The lower the HC concentration relative to Gas Mix 3, the greater the difference between the group means and the expected value. For example, the group means for Gas Mix 1 ranged from about 9 to 11 % lower than the expected value, while the means for Gas Mix 5 ranged from about 20 to 24 % lower. For Gas Mix 4, which had a higher HC concentration than that of Gas Mix 3, the group means were about 1 to 8 % higher than the expected value. Note that this result is the reverse of what occurred with CO measurements using the RSD-1000 unit in Experiment 1, above. The precision for these measurements was fairly good. For Gas Mixes 1-4, the group standard deviations were no more than about 5 % of the means; for Gas Mix 5, about 5 to 10 %. A linear fit of the means gave an excellent r^2 of 0.998.

Again, the NO/CO_2 group means (Table 6b) were inconsistent. The measured values for the *calibration gas* (Gas Mix 3) were *about 30 to 32 % lower* than the expected value. This was the worst discrepancy; the worst of the remaining discrepancies were in the test with Gas Mix 4, in which the NO/CO_2 group means were about 13 to 20 % lower than the expected value. On the other hand, in the test with Gas Mix 1, the NO/CO_2 group means were somewhat (about 3 to 11 %) *higher* than the expected value. The precision again was not as good as the measurements with HCs. The standard deviations for the Gas Mix 1 data ranged from about 5 to 8 % of the group means, while those for the calibration gas (Gas Mix 3) ranged from about 8 to 16 % of the means. Despite all this, a linear fit of the means gave an r^2 of 0.969; however, a third order polynomial was required to give a fit comparable to the CO and HC linear fits (an r^2 of 0.992).

Table 6b. Puff Test Results for the Smog Dog™ 3 Calibrated with Gas Mix 3

Gas Mix	Group	N	CO/CO_2 Ratio			HC/CO_2 Ratio			NO/CO_2 Ratio		
			Expected	Mean	Std Dev	Expected	Mean	Std Dev	Expected	Mean	Std Dev
1	1	25	0.226316	0.220328	0.010525	0.032308	0.028736	0.000838	0.031105	0.033328	0.002242
	2	25	0.226316	0.21486	0.004770	0.032308	0.028876	0.000459	0.031105	0.032112	0.002688
	3	25	0.226316	0.225448	0.008027	0.032308	0.02936	0.000802	0.031105	0.034448	0.002577
	4	25	0.226316	0.221532	0.007640	0.032308	0.029252	0.000468	0.031105	0.032364	0.001614
2	1	25	0.333333	0.320456	0.002172	0.0100	0.008956	0.000126	0	-0.0043	0.000473
	2	25	0.333333	0.314056	0.001543	0.0100	0.008364	0.000104	0	-0.00425	0.00048
	3	25	0.333333	0.319396	0.002263	0.0100	0.00868	0.000096	0	-0.00422	0.000347
	4	25	0.333333	0.320948	0.001754	0.0100	0.00882	0.0001	0	-0.0043	0.000459
3	1	25	0.611006	0.600412	0.004593	0.060246	0.059468	0.000309	0.014232	0.009916	0.000994
	2	25	0.611006	0.607348	0.005276	0.060246	0.0603	0.000509	0.014232	0.009672	0.00099
	3	25	0.611006	0.608776	0.004466	0.060246	0.060268	0.000348	0.014232	0.010032	0.000787
	4	25	0.611006	0.615264	0.009277	0.060246	0.060628	0.000644	0.014232	0.00994	0.001629
4	1	25	1.006662	1.0025	0.038798	0.132578	0.1342	0.006391	0.02545	0.022084	0.001574
	2	25	1.006662	1.005116	0.020561	0.132578	0.139104	0.001752	0.02545	0.021132	0.00118
	3	25	1.006662	1.010736	0.019138	0.132578	0.135936	0.004575	0.02545	0.021572	0.001451
	4	25	1.006662	0.993236	0.040287	0.132578	0.142988	0.001932	0.02545	0.020252	0.00212
5	1	25	0.071429	0.072904	0.001233	0.002143	0.001632	0.000080	0	-0.00061	0.00055
	2	25	0.071429	0.075628	0.001774	0.002143	0.001704	0.000093	0	-0.00054	0.000535
	3	25	0.071429	0.075728	0.001875	0.002143	0.001712	0.000174	0	-0.00079	0.001008
	4	25	0.071429	0.074008	0.001786	0.002143	0.001636	0.000104	0	-0.00070	0.000614

Gas Mix 4 as the Calibration Gas (Table 6c) -- In this set of tests, the CO/CO_2 group means were all underestimates of the expected value, although they were all less than 9 % low. The standard deviations were about 1 to 2 % of the group means for Gas Mixes 1-4, and less than 5 % of the means for Gas Mix 5. Not surprisingly, a linear fit of the means gave an excellent r^2 of 0.999.

On the other hand, with the exception of the test with Gas Mix 4 (the calibration gas), the HC/CO_2 group means were considerably lower than the expected values. The worst discrepancy was for Gas Mix 5, where the measured mean values were 36 to 47 % lower than the expected value. (Note that the HC concentration in the calibration gas was higher than that of Gas Mix 5, so this result is again the reverse of what occurred with CO measurements using the RSD-1000 unit in Experiment 1, above.) However, the precision of the data was quite good; the standard deviations for the data groups were all less than 3 % of their means. A linear fit of the means gave an excellent r^2 of 0.995.

The NO/CO_2 group means were consistently lower than the expected values. The means for the *calibration gas* (Gas Mix 4) were *about 22 to 24 % lower* than the expected value. However, the worst discrepancy was in the test with Gas Mix 3, in which the NO/CO_2 group means were about 28 to 33 % lower than the expected value. Again, the precision of the data was not as good as that for CO and HCs. The standard deviations were less than 5 % of the means for Gas Mixes 1 and 4, but were about 12 to 18 % of the means for Gas Mix 3. A linear fit of the means gave an r^2 of 0.977; however, a second order polynomial was required to give a fit comparable to those for the CO and HC data (an r^2 of 0.99).

Table 6c. Puff Test Results for the Smog Dog™ 3 Calibrated with Gas Mix 4

Gas Mix	Group	N	CO/CO_2 Ratio			HC/CO_2 Ratio			NO/CO_2 Ratio		
			Expected	Mean	Std Dev	Expected	Mean	Std Dev	Expected	Mean	Std Dev
1	1	25	0.226316	0.212072	0.002554	0.032308	0.02446	0.00059	0.031105	0.02958	0.001031
	2	25	0.226316	0.211192	0.004265	0.032308	0.023632	0.0001029	0.031105	0.029392	0.001322
	3	25	0.226316	0.216196	0.003094	0.032308	0.024436	0.000603	0.031105	0.02938	0.000737
	4	25	0.226316	0.211892	0.002862	0.032308	0.024552	0.000552	0.031105	0.02892	0.000794
2	1	25	0.333333	0.31372	0.00367	0.01000	0.006432	0.000107	0	-0.00253	0.000628
	2	25	0.333333	0.308068	0.005505	0.01000	0.006388	0.000088	0	-0.00276	0.000586
	3	25	0.333333	0.31432	0.00421	0.01000	0.006636	0.000091	0	-0.00256	0.000477
	4	25	0.333333	0.312668	0.003242	0.01000	0.006456	0.000082	0	-0.00256	0.000286
3	1	25	0.611006	0.575516	0.009051	0.060247	0.051328	0.000699	0.014232	0.010012	0.001219
	2	25	0.611006	0.584508	0.007877	0.060247	0.053952	0.000667	0.014232	0.010236	0.001268
	3	25	0.611006	0.572292	0.00635	0.060247	0.051964	0.000797	0.014232	0.00958	0.001157
	4	25	0.611006	0.577436	0.009468	0.060247	0.051076	0.001131	0.014232	0.009484	0.001672
4	1	25	1.006662	0.994116	0.005975	0.132578	0.133064	0.000402	0.02545	0.0198	0.000806
	2	25	1.006662	1.002756	0.004405	0.132578	0.133572	0.000629	0.02545	0.019688	0.000655
	3	25	1.006662	0.99802	0.006271	0.132578	0.132788	0.000651	0.02545	0.019844	0.000601
	4	25	1.006662	0.99568	0.004791	0.132578	0.133164	0.000476	0.02545	0.019416	0.000581
5	1	25	0.071429	0.065104	0.001491	0.002143	0.001144	0.000058	0	0.000192	0.00055
	2	25	0.071429	0.067464	0.002041	0.002143	0.001236	0.000182	0	0.000064	0.000535
	3	25	0.071429	0.068244	0.003176	0.002143	0.001188	0.000322	0	0.000072	0.001008
	4	25	0.071429	0.068636	0.001835	0.002143	0.00138	0.000168	0	-0.00023	0.000614

Experiment 3

A summary of the puff test results for the three RSDs is shown in Tables 7a-7c, below. The Group number designates a series of puffs that were initiated after each device was calibrated, and N indicates the number of puffs in each Group. The means and standard deviations (Std Dev) of the CO/CO_2,HC/CO_2,and NO/CO_2 ratios are shown for each series of puffs and for each device. Note that prior to these tests, the RSD-1000 software had been upgraded, an improvement over that used in Experiment 1, above.

Although the main objective of this series of puff tests was to evaluate the capability of RSDs to measure NO emissions (the CO and HC concentrations in all three test gases were essentially unvaried), it is interesting to note the response of the instruments to CO and HCs.

As shown in Table 7a, the CO/CO_2 group means for the FEAT #3008 were both higher and lower than the expected values for the three test gases; the standard deviations for the data groups ranged from about 7 to about 20 % of the mean values. The CO/CO_2 group means for the RSD-1000 were always slightly more than the expected values; the standard deviations for the data groups were less than 10 % of the mean values. [Note that this was despite the fact that the calibration gas values were about 10 times the test gas values, indicating that the bias shown in the earlier puff tests with the RSD-1000 (Experiment 1, above) had been corrected by the software upgrade.] However, the CO/CO_2 group means for the Smog Dog™ 3 were always considerably greater than the expected values; i.e., about 60-90 % greater. The standard deviations for the Smog Dog™ 3 data groups were similar (relative to the mean values) to those of the FEAT #3008.

Table 7a. RSD Puff Measurements -- CO/CO_2 Ratios

Gas Mix	Group	Expected	FEAT #3008			RSD-1000			Smog Dog™ 3		
			N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev
1	1	0.0199867	25	0.018311	0.001421	25	0.018737	0.000934	24	0.032188	0.001556
	2	0.0199867	25	0.021552	0.002491	25	0.018748	0.00091	27	0.033856	0.001618
	3	0.0199867	25	0.019603	0.002264	25	0.018843	0.000858	28	0.032929	0.001736
	4	0.0199867	25	0.022407	0.004033	25	0.018709	0.000869	28	0.033693	0.002381
2	1	0.0200133	25	0.020026	0.002608	25	0.019246	0.001041	25	0.032108	0.002329
	2	0.0200133	25	0.020834	0.00193	25	0.018696	0.000756	24	0.032654	0.002348
	3	0.0200133	25	0.020429	0.00262	25	0.018934	0.000947	26	0.038365	0.005379
	4	0.0200133	25	0.021846	0.002132	25	0.018907	0.00104	29	0.031797	0.006439
3	1	0.0199933	25	0.022123	0.002294	25	0.019771	0.001451	26	0.033385	0.001451
	2	0.0199933	25	0.0198	0.003006	25	0.018684	0.001425	30	0.034437	0.002271
	3	0.0199933	25	0.019829	0.00208	25	0.019844	0.001459	27	0.033874	0.001993
	4	0.0199933	25	0.021353	0.002013	25	0.019657	0.000857	27	0.034415	0.001104

The pattern for the HC/CO_2 group means (Table 7b) was similar to those for the

CO/CO_2. The HC/CO_2 group means for the FEAT #3008 were both higher and lower than the expected values for the three test gases, although over a considerably greater range than for CO/CO_2. Specifically, they ranged from about 8 % less to about 25 % more than the expected values. The standard deviations for the data groups ranged from about 11 to 22 % of the mean values.

The HC/CO_2 group means for the RSD-1000 were consistently higher (11 to 22 % higher) than the expected values for the three test gases. The standard deviations for the RSD-1000 data groups ranged from about 5 to 15 % of the mean values. The HC/CO_2 group means for the Smog Dog™ 3 were also consistently higher than the expected values for the three test gases, but by a wider margin; specifically, about 19 to 45 % higher. The standard deviations for the Smog Dog™ 3 data groups ranged from about 8 to 22 % of the mean values, again, similar to the FEAT #3008 results.

Table 7b. RSD Puff Measurements -- HC/CO_2 Ratios

Gas Mix	Group	Expected	FEAT #3008			RSD-1000			Smog Dog™ 3		
			N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev
1	1	0.003331	25	0.003062	0.000523	25	0.003702	0.000259	24	0.003971	0.0006
	2	0.003331	25	0.003592	0.000541	25	0.003703	0.000261	27	0.004211	0.000404
	3	0.003331	25	0.0036	0.000668	25	0.003829	0.000262	28	0.004204	0.00042
	4	0.003331	25	0.00426	0.000952	25	0.003798	0.000211	28	0.004214	0.000619
2	1	0.003509	25	0.004156	0.000682	25	0.003932	0.000263	25	0.004052	0.000418
	2	0.003509	25	0.003852	0.000411	25	0.003841	0.000299	24	0.004179	0.000551
	3	0.003509	25	0.004036	0.000548	25	0.00396	0.000264	26	0.004815	0.00069
	4	0.003509	25	0.003994	0.000671	25	0.004051	0.000277	29	0.004169	0.000919
3	1	0.003347	25	0.003789	0.000871	25	0.003843	0.000562	26	0.004219	0.000343
	2	0.003347	25	0.004038	0.000685	25	0.00371	0.000351	30	0.004037	0.000487
	3	0.003347	25	0.003889	0.000651	25	0.003962	0.000398	27	0.004337	0.000463
	4	0.003347	25	0.003698	0.000832	25	0.003891	0.000229	27	0.0042	0.000348

FEAT #3008 NO/CO_2 Values -- As shown in Table 7c, the NO/CO_2 group means for the FEAT #3008 were both higher and lower than the expected values for the three test gases, but over a higher range than for HC/CO_2. Relative to the expected values, the group means were:

for Gas Mix 1, - 26 to + 30 %;
for Gas Mix 2, - 11 to + 22 %; and
for Gas Mix 3, - 19 to + 6 %.

The standard deviations for the FEAT #3008 data groups were considerably higher than those for both CO/CO_2 and HC/CO_2. Relative to the means, they were:

for Gas Mix 1, 51 to 140 %;
for Gas Mix 2, 31 to 49 %; and
for Gas Mix 3, 29 to 41 %.

As might be expected, as the expected NO/CO_2 value increased, the deviation of the means of the data group from the expected value decreased, and the variability of the data decreased. A linear fit of a plot of the NO/CO_2 means resulted in an r^2 of 0.883.

RSD-1000 NO/CO_2 Values -- The NO/CO_2 group means for the RSD-1000 were both higher and lower than the expected values for the gas mixes 1 and 3, but were always higher for gas mix 2. Although not as large a range of differences as was exhibited by the FEAT #3008, the range was greater than that exhibited by the RSD-1000 for HC/CO_2. Specifically, relative to the expected values, the group means were:

for gas mix 1, - 2 to + 13 %;
for gas mix 2, + 17 to + 22 %; and
for gas mix 3, - 2 to + 45 %.

The standard deviations for the RSD-1000 data groups were higher than those for both CO/CO_2 and HC/CO_2. Relative to the means, they were:

for gas mix 1, 21 to 29 %;
for gas mix 2, 20 to 37 %; and
for gas mix 3, 16 to 20 %.

Unlike the results for the FEAT #3008, as the actual (expected) NO/CO_2 value increased, the deviation of the means of the data group from the actual value actually *increased*. In addition, the variability of the data actually increased in the tests for gas mix 2, when compared to the results of the tests for gas mix 1. However, for gas mix 3, the variability of the data decreased. A linear fit of a plot of the NO/CO_2 group means resulted in an r^2 of 0.926, somewhat better than the fit for the FEAT #3008 data.

Smog Dog™ 3 NO/CO_2 Values -- The NO/CO_2 group means for the Smog Dog™ 3 were consistently higher than the expected values for all three gas mixes. Although the differences from the expected values were somewhat higher than those for HC/CO_2, they were lower than those for CO/CO_2. The differences were, overall, larger than those for both the FEAT #3008 and the RSD-1000. Specifically, relative to the expected values, the group means were:

for gas mix 1, 37 to 64 %;
for gas mix 2, 31 to 52 %; and
for gas mix 3, 26 to 35 %.

The standard deviations for the Smog Dog™ 3 data groups, relative to the means, were considerably higher than those for both CO/CO_2 and HC/CO_2 for gas mixes 1 and 2, but lower for gas mix 3. Relative to the means, they were:

for gas mix 1, 25 to 57 %;
for gas mix 2, 20 to 41 %; and
for gas mix 3, 9 to 11 %.

As with the FEAT #3008, as the expected NO/CO_2 value increased, the deviation of the means of the Smog Dog™ 3 data group from the actual value decreased, and the variability of the data decreased. A linear fit of a plot of the NO/CO_2 group means resulted in an r^2 of 0.981, which was a better fit than data from either of the other two devices.

In summary, with group means both above and below the actual values, the mean of all the FEAT #3008 NO/CO_2 data (100 measurements for each gas mix) was the most accurate. Except for the RSD-1000 test with gas mix 1, the means of the data for the RSD-1000 and the Smog Dog™ 3 were overestimates of the actual values. However, with the exception of the RSD-1000 test with gas mix 3, the precision of the FEAT #3008 was not as good as the other two devices. On the other hand, while the Smog Dog™ 3 exhibited consistent precision, its overall accuracy was not as good in these NO puff tests relative to the other two devices. Nevertheless, because all three devices responded in essentially a linear manner to the increases in NO concentration, they appeared to be adequate for this application. Therefore, dynamometer, track, and road tests were subsequently conducted.

Table 7c. RSD Puff Measurements -- NO/CO_2 Ratios

Gas Mix	Group	Expected	FEAT #3008			RSD-1000			Smog Dog™ 3		
			N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev
1	1	0.003331	25	0.004028	0.002048	25	0.003254	0.000773	24	0.005475	0.001992
	2	0.003331	25	0.004341	0.005763	25	0.003756	0.000787	27	0.005389	0.001534
	3	0.003331	25	0.00247	0.003461	25	0.003588	0.001043	28	0.005164	0.00128
	4	0.003331	25	0.003184	0.003794	25	0.003562	0.001042	28	0.004564	0.002619
2	1	0.006664	25	0.007281	0.003573	25	0.008565	0.001713	25	0.00876	0.001767
	2	0.006664	25	0.005921	0.002982	25	0.007779	0.001751	24	0.009654	0.002353
	3	0.006664	25	0.007742	0.002519	25	0.00805	0.001735	26	0.010154	0.004176
	4	0.006664	25	0.008104	0.002503	25	0.008305	0.00309	29	0.009314	0.003399
3	1	0.009973	25	0.010558	0.003434	25	0.014437	0.002438	26	0.012569	0.001102
	2	0.009973	25	0.00803	0.003277	25	0.012475	0.002455	30	0.0134	0.001509
	3	0.009973	25	0.01062	0.004126	25	0.009809	0.001537	27	0.012896	0.001342
	4	0.009973	25	0.009715	0.002794	25	0.011741	0.002084	27	0.013444	0.001225

Experiment 4

The results of the dynamometer testing are summarized in Table 8. The means and standard deviations (Std Dev) of the CO/CO_2, HC/CO_2, and NO/CO_2 ratios are shown for each vehicle test. The intent was to conduct a series of three tests with each vehicle. However, because of problems in the first series of tests with the Mustang, it was subjected to a second series of tests to obtain NO data that could be used in the comparisons to the track test data. As stated earlier, the results of the dynamometer testing were assumed to be the actual emissions from the vehicles, or the “standards” by which the track results would be measured.

Table 8 . Summary of Second-by-Second Emissions During Dynamometer Testing

Vehicle	Test #	Time (sec)	CO/CO_2		HC/CO_2		NO/CO_2	
			Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Ford Mustang II	1	481	0.000118	0.000061	0.000579	0.000089	NA	NA
Ford Mustang II	2	481	0.000018	0.000049	0.000543	0.000061	NA	NA
Ford Mustang II	3	481	0.000075	0.000369	0.000588	0.000119	NA	NA
Ford Mustang II	4	481	NA	NA	NA	NA	0.015359	0.000325
Ford Mustang II	5	440	NA	NA	NA	NA	0.014501	0.001808
Ford Mustang II	6	481	NA	NA	NA	NA	0.014341	0.001442
Ford F-150 Truck	1	481	0.000632	0.000430	0.000830	0.000031	0.003517	0.000306
Ford F-150 Truck	2	481	0.000364	0.000587	0.000862	0.000050	0.003705	0.000212
Ford F-150 Truck	3	481	0.000517	0.000439	0.000980	0.000060	0.003683	0.000228
Dodge Caravan	1	481	0.012875	0.005070	0.001290	0.000517	0.001055	0.000721
Dodge Caravan	2	481	0.010857	0.004651	0.000976	0.000401	0.001015	0.000702
Dodge Caravan	3	481	0.011414	0.007296	0.000995	0.000547	0.001087	0.000702

Note: NA indicates that data were unavailable from second-by-second testing.

Again, the main objective of this series of tests was to ultimately evaluate the capability of RSDs to measure NO emissions; however, it is interesting to note all the relative emissions of the three vehicles. The average CO/CO_2 ratio was the highest for the Caravan (~10^{-2}), almost two orders of magnitude higher than that of the F-150 (~$2x10^{-4}$), which was higher than that of the Mustang. However, the mean CO/CO_2 ratios for the Mustang were also highly variable (~$2x10^{-5}$ to 10^{-4}). The same relative order held for the HC/CO_2 ratios (Mustang lowest, Caravan highest), although the range of the means was much less (~$6x10^{-4}$ to 10^{-3}). For the NO/CO_2 ratios, the relative order was reversed (Caravan lowest, Mustang highest).

The relative precision of the data was also interesting. For the CO/CO_2 ratios, the *lowest* standard deviation relative to the mean was for the Caravan at 39 % [(0.005070/0.0128750x100], while the highest was for the Mustang at *492 %* [(0.000369/0.000075)x100]. Note, however, that the CO/CO_2 means for the Mustang were lower than those for the F-150, and much lower than those for the Caravan. Note also that, for the HC/CO_2 and NO/CO_2 ratios, relative to the means, the standard deviations were lower overall when compared with the CO/CO_2 data. These ranged from about 2 % -- one of the NO/CO_2 ratios for the Mustang -- to 69 % -- one of the NO/CO_2 ratios for the Caravan. In fact, the relative precision of the Caravan HC and NO emission data was considerably worse than that of the other two vehicles. In addition, while these data for the Mustang and F-150 were considerably more precise than their CO data, all of the Caravan data had about the same precision. Relative to the means, they were:

for CO/CO_2, 39 to 64 %;
for HC/CO_2, 40 to 55 %; and
for NO/CO_2, 65 to 69 %.

Note that the CO/CO_2 ratios for the Caravan were *higher* than those of the other two vehicles, and these data represented the *best* precision. On the other hand, the NO/CO_2 ratios for the Caravan were *lower* than those of the other two vehicles, and these data represented the *worst* precision. Assuming a proportional bias in the instrumentation at the dynamometer facility, this would possibly explain the numbers above. However, the fact is that the HC/CO_2 ratios for the Caravan were *similar* to those of the other two vehicles ($\sim10^{-3}$), but these data *also represented the worst precision*. Although there may have been differences in the behavior of the Caravan on the dynamometer or in the driver's handling of the vehicle, there is no clear reason for this anomaly.

For the other two vehicles, the standard deviations for the NO/CO_2 data relative to the means were:

for the Mustang, 2 to 13 %; and
for the F-150, 6 to 9 %.

Note, however, that because the NO/CO_2 means for the Mustang were about four times as high as those for the F-150, and an order of magnitude higher than those for the Caravan, the actual variation in the NO/CO_2 data was higher for the Mustang than for either of the other two vehicles.

It should be noted that the Mustang was tested twice. During the first series of tests (1-3), the NO measurements exceeded the range for which the instrumentation had been set. For this reason, a separate series of tests (4-6) was conducted, during which only the NO was measured. Because of probable changes in fuel -- as well as changes in the condition (e.g., tuning) and operation of the vehicle -- the combination of CO and HC measurements may or may not be comparable to the NO measurements.

Experiment 5

The results of the track testing are summarized in Tables 9a-9c. The Group number designates a series of laps that were made by the vehicles around the track, and N indicates the number of laps in each group. After each group of laps, all three instruments were recalibrated. The means and standard deviations (Std Dev) of the CO/CO_2, HC/CO_2, and NO/CO_2 ratios are shown for each group.

The average of the means of the four groups of CO/CO_2 track data for the Mustang and F-150 from all three RSDs (Table 9a) was about two orders of magnitude greater than the average of the three groups of CO/CO_2 dynamometer data (Table 8). However, the CO/CO_2 track data for the Caravan from the FEAT #3008 and the RSD-1000 were very similar to the corresponding dynamometer data. The Smog Dog™ 3 CO/CO_2 track data for the Caravan were all lower than the corresponding dynamometer data.

Table 9a. RSD Measurements at the Track -- CO/CO_2 Ratios

Vehicle	Group	FEAT #3008			RSD-1000			Smog Dog™ 3		
		N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev
Ford Mustang II	1	27	0.007098	0.013453	27	0.011	0.024404	22	0.009682	0.023507
	2	30	0.006296	0.012869	30	0.003967	0.003409	24	0.00145	0.005705
	3	27	0.006295	0.011272	27	0.005	0.011923	25	0.002388	0.007591
	4	27	0.006849	0.014061	27	0.006185	0.008458	27	0.003804	0.007228
Ford F-150 Truck	1	27	0.005942	0.009736	27	0.004556	0.006154	23	0.000404	0.014203
	2	30	0.045064	0.029773	30	0.030433	0.023242	25	0.03448	0.036575
	3	27	0.025625	0.030056	27	0.018667	0.02301	27	0.011722	0.029716
	4	27	0.005687	0.008443	27	0.00463	0.004508	26	-0.00045	0.01301
Dodge Caravan	1	27	0.016204	0.018283	27	0.012296	0.011864	19	-0.00547	0.017234
	2	30	0.016648	0.017414	30	0.011733	0.00762	24	-0.0031	0.01561
	3	27	0.016406	0.027429	27	0.013481	0.012119	21	-0.01006	0.017086
	4	27	0.021827	0.016425	27	0.012593	0.008824	21	-0.01026	0.015637

The average of the means of the four groups of the FEAT #3008 HC/CO_2 track data for the Mustang (Table 9b) was about an order of magnitude greater than the average of the three groups of CO/CO_2 dynamometer data (see Table 8), while the RSD-1000 track data for the Mustang averaged about twice the corresponding dynamometer data. On the other hand, the Smog Dog™ 3 HC/CO_2 track data for the Mustang averaged about a third (over 60 % lower) of the corresponding dynamometer data. For the F-150, the FEAT #3008 HC/CO_2 track data averaged about four times the corresponding dynamometer data, while data from the other two RSDs averaged lower than the same data. Specifically, the RSD-1000 data averaged about 42 % lower, while the Smog Dog™ 3 data averaged more than 300 % lower (all of the group means were less than zero; Table 9b). A similar pattern occurred for the Caravan data; the FEAT #3008 data averaged about seven times the corresponding dynamometer data, while data from the RSD-1000 and Smog Dog™ 3 averaged almost 200 % and almost 400 % lower, respectively (both averages less than zero).

Table 9b. RSD Measurements at the Track -- HC/CO_2 Ratios

Vehicle	Group	FEAT #3008			RSD-1000			Smog Dog™ 3		
		N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev
Ford Mustang II	1	27	0.003606	0.002441	27	0.001481	0.001451	22	0.000155	0.001451
	2	30	0.003202	0.005508	30	0.0001	0.003021	24	-0.0004	0.001422
	3	27	0.005687	0.003333	27	0.000481	0.003043	25	0.000224	0.001556
	4	27	0.006818	0.004629	27	0.002074	0.003802	27	0.000693	0.002769
Ford F-150 Truck	1	27	0.003684	0.001562	27	0.000815	0.000879	23	-0.00145	0.002847
	2	30	0.001341	0.015595	30	-0.00017	0.00278	25	-0.00208	0.015996
	3	27	0.004815	0.003408	27	0.000593	0.001366	27	-0.00177	0.00273
	4	27	0.004509	0.002034	27	0.000815	0.000736	26	-0.00217	0.001839
Dodge Caravan	1	27	0.005563	0.002558	27	0.000296	0.001514	19	-0.00291	0.003091
	2	30	0.005596	0.014159	30	-0.00427	0.009512	24	-0.00256	0.00825
	3	27	0.008643	0.006292	27	-0.00074	0.002566	21	-0.00395	0.004102
	4	27	0.00824	0.004577	27	0.00063	0.001597	21	-0.00285	0.003018

The average of the means of the four groups of NO/CO_2 track data for the Mustang and F-150 from all three RSDs (Table 9c) was the same order of magnitude of the average of the three groups of NO/CO_2 dynamometer data (see Table 8). However, the data for the Mustang tended to be higher (e.g., the Smog Dog™ 3 data averaged over 40 % higher than the corresponding dynamometer data), while the data for the F-150 tended to be lower (e.g., the RSD-1000 data averaged over 56 % lower than the corresponding dynamometer data). For the Caravan, the pattern that occurred in the HC/CO_2 data reoccurred. Specifically, the FEAT #3008 data averaged about six times the corresponding dynamometer data, while data from the RSD-1000 and Smog Dog™ 3 averaged over 150 % and over 350 % lower, respectively (both averages less than zero).

Table 9c. RSD Measurements at the Track -- NO/CO_2 Ratios

Vehicle	Group	FEAT #3008			RSD-1000			Smog Dog™ 3		
		N	Mean	Std Dev	N	Mean	Std Dev	N	Mean	Std Dev
Ford Mustang II	1	27	0.0144	0.018402	27	0.020481	0.015875	22	0.019168	0.007188
	2	30	0.020002	0.020642	30	0.014833	0.014264	24	0.023333	0.008344
	3	27	0.019366	0.015082	27	0.012556	0.019025	25	0.021152	0.005972
	4	27	0.017844	0.01694	27	0.010222	0.016073	27	0.021189	0.008319
Ford F-150 Truck	1	27	0.001477	0.015551	27	0.003111	0.008345	23	0.004091	0.013821
	2	30	0.003879	0.018353	30	0.001633	0.016407	25	0.000056	0.013567
	3	27	0.002939	0.015819	27	0.001963	0.007793	27	0.000148	0.012636
	4	27	0.000691	0.007877	27	-0.00033	0.00826	26	0.003135	0.009825
Dodge Caravan	1	27	0.00357	0.01366	27	-0.00033	0.010058	19	-0.00351	0.008331
	2	30	0.021506	0.026348	30	-0.0032	0.017327	24	-0.00082	0.015213
	3	27	0.00162	0.025439	27	-0.00252	0.01458	21	-0.00084	0.016217
	4	27	-0.00188	0.018392	27	0.003037	0.013523	21	-0.00597	0.014484

The inconsistency in all these data cannot be readily explained, but there were a number of factors to take into consideration; e.g.,

(a) The grade of the track was very slight (almost flat), making it very difficult to have some pressure on the accelerator without exceeding the 45 mph speed target. The F-150 was the only vehicle with cruise control, but it was noted that the engine revolutions per minute (RPM) were at a variety of levels as the vehicle passed the RSDs.

(b) The height of the exhaust above the road, and the location of the exhaust (behind or to the side) varied from vehicle to vehicle. Specifically, the F-150 exhaust was the highest above the road, while the Caravan exhaust was located on the right rear of the vehicle. The RSDs had to be adjusted several times to detect all three vehicles.

Experiment 6

Because all three of the RSDs did not always "see" a specific vehicle, the data had to be screened to identify those vehicles for which emission data were available for all three RSDs. In addition, because of uncertainty in data for each individual vehicle and RSD combination, a "one-on-one" comparison between the data from, say, RSD X for Vehicle A to that from RSD Y for the same vehicle is not meaningful. So, it was decided that the range of measurements by the three RSDs of the "fleet," or entire sample of vehicles would be grouped in intervals, or "binned,"and the distribution of the measurements displayed. The results of the road testing, then, are summarized in Figures 5a-5c. The figures show the fraction of the fleet (on a logarithmic scale) which falls in each interval of CO/CO_2, HC/CO_2, and NO/CO_2, respectively.

The CO/CO_2, HC/CO_2, and NO/CO_2 data each appear to have quite different distributions. However, within a particular figure, the distributions of data for each RSD appear to be similar to one another. The only data which appear to be distributed in a near-normal manner are those for NO/CO_2. Note that most of the fleet emissions, for both HC/CO_2 and NO/CO_2, are near zero.

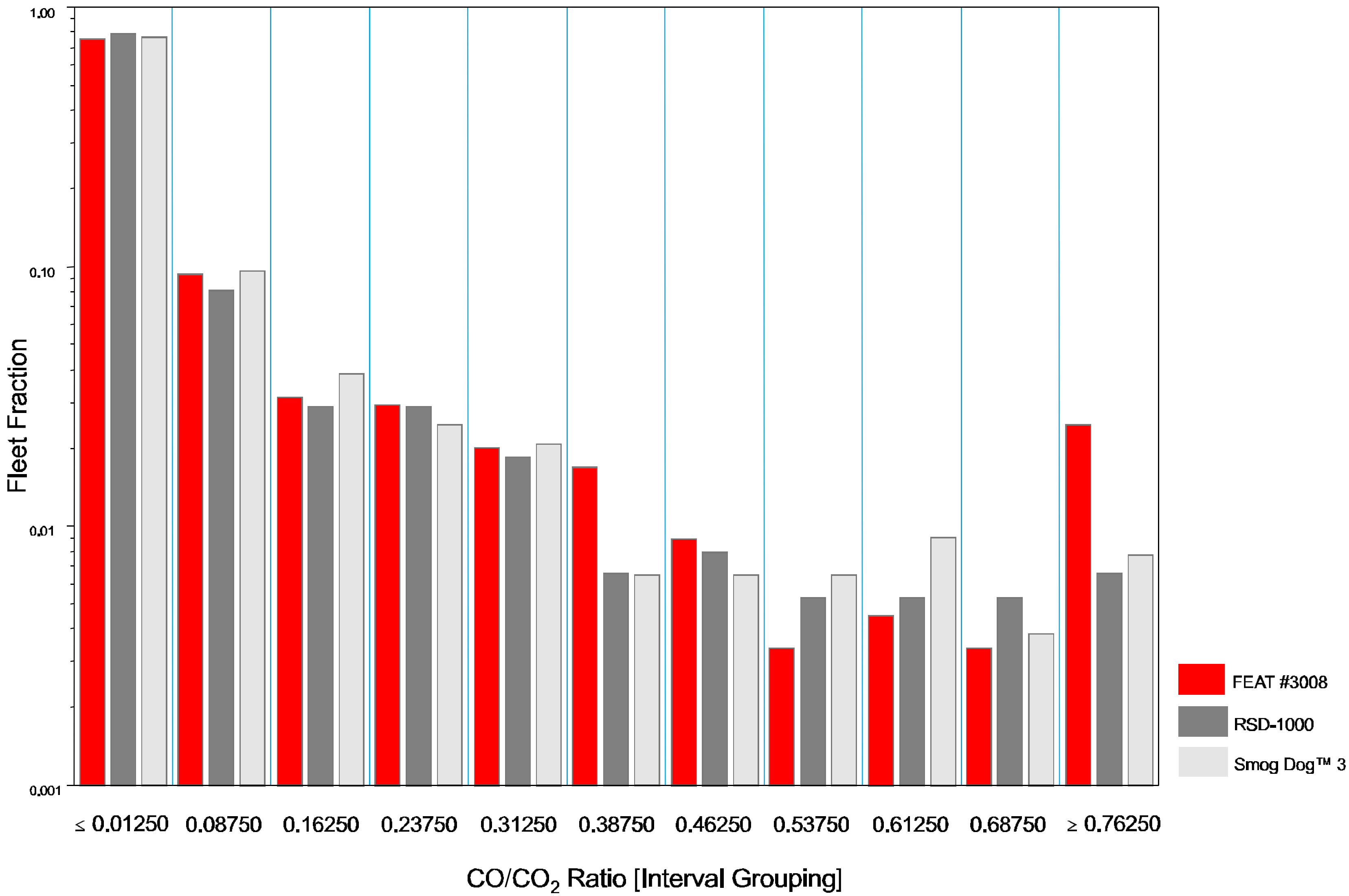


Figure 5a. Distribution of CO/CO_2 emissions data for motor vehicles measured by RSDs at freeway entrance in Raleigh, NC.

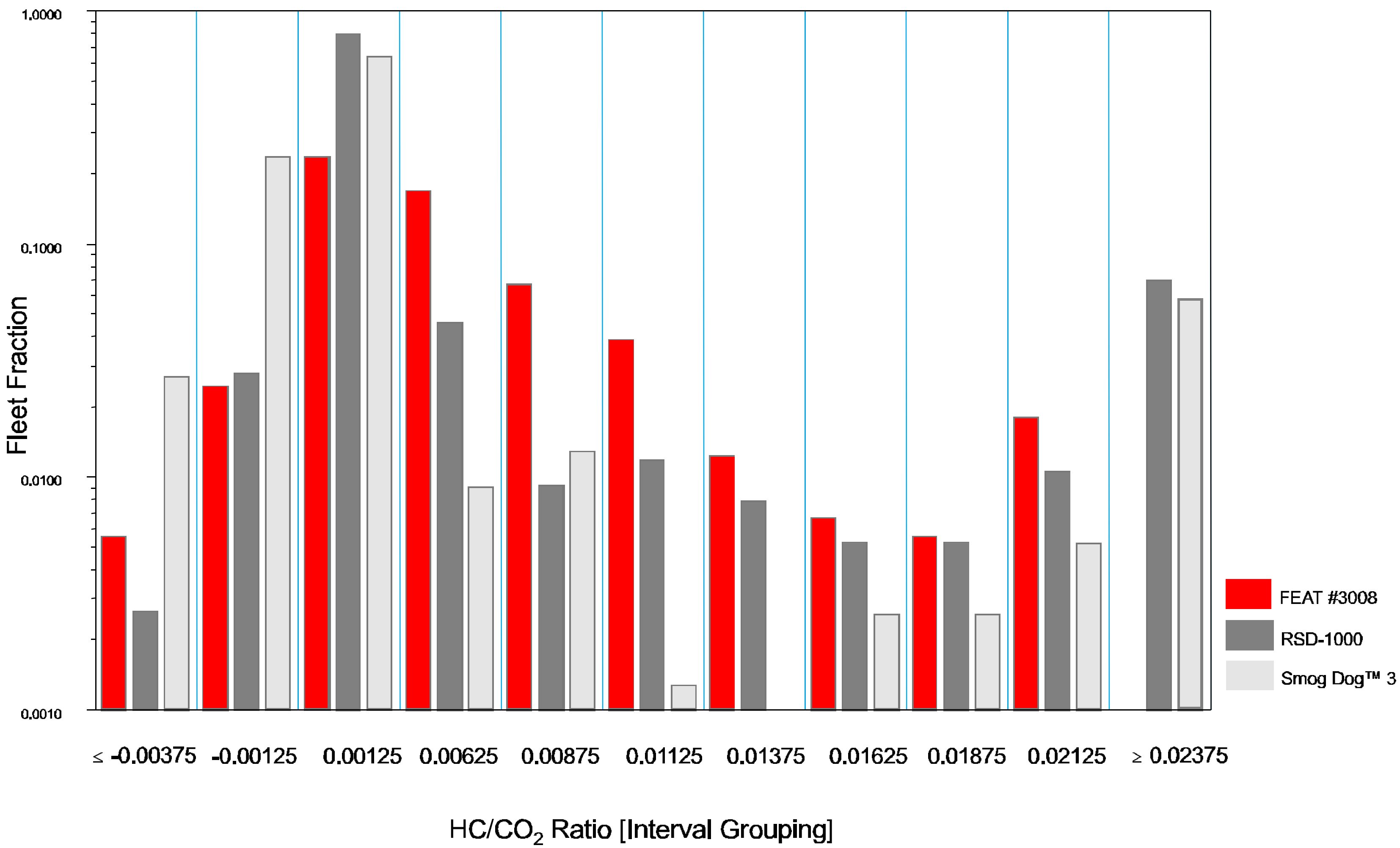


Figure 5b. Distribution of HC/CO_2 emissions data for motor vehicles measured by RSDs at freeway entrance in Raleigh, NC.

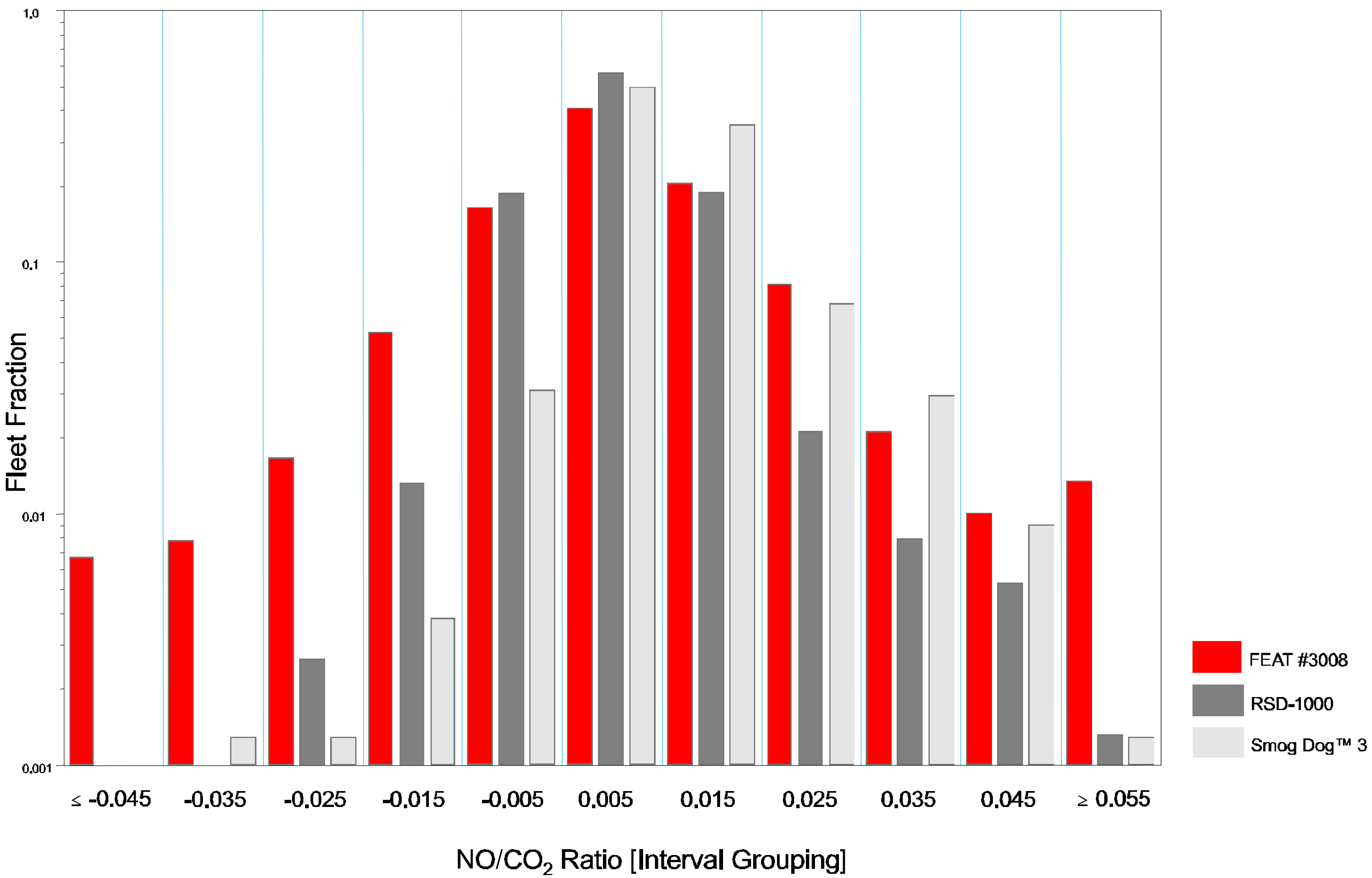


Figure 5c. Distribution of NO/CO_2 emissions data for motor vehicles measured by RSDs at freeway entrance in Raleigh, NC.

CONCLUSIONS

RSDs represent a method for collecting data on emissions from a large number of motor vehicles in a relatively short period of time. The tests described in this report represent an attempt to better understand the capabilities of RSDs and the quality of the data that they can provide.

The accuracy and precision of RSD measurements made in the puff tests (Experiments 1-3), although showing a generally linear response over a range of CO, HC, and NO concentrations, did not necessarily indicate how the RSDs would perform in the field. For example, the puff tests showed that the precision and accuracy of the RSD data were in the following order:

$$CO/CO_2 > HC/CO_2 > NO/CO_2$$

However, the average track data for each of the three vehicles (Experiment 5) when compared to the corresponding dynamometer data (Experiment 4), show quite a different result. With the exception of the CO/CO_2 data for the Caravan, the accuracy of the RSD track data, using the dynamometer data as the "standard," showed just the opposite result; i.e.,

$$NO/CO_2 > HC/CO_2 > CO/CO_2$$

On the other hand, the track data showed a considerable amount of variation (Tables 9a-c). Whether or not this was caused by the conditions at the site (e.g., the slight grade) or some other variable is a question for possible future research. This could include testing of a small number of vehicles at another location (on the same track or elsewhere) with a steeper grade, where a constant speed could be more easily maintained. Unfortunately, what is unclear at this writing is the effect, if any, that differences between individual sites have on the quality of the data collected.

Because of the experience at the track, the differences in readings by the three RSDs for each individual vehicle in the road tests (Experiment 6) -- where each vehicle was "seen" only once by the equipment -- were not surprising. This uncertainty in each individual measurement was the reason for presenting the data the way that they are in Figures 5-7, above. Nevertheless, as noted in the discussion for the road tests, the distributions of data for each RSD are similar. This supports the conclusion that, if enough data are collected, they should serve as an adequate indication of the fleet emissions at a particular location. In addition, if testing is conducted at enough sites in a metropolitan area, the data should provide an adequate indication of that area's fleet emissions.

Finally, the results in this report represent an initial set of analyses. More detailed statistical analyses of these data should provide additional understanding.

REFERENCES

1. Stephens, R.D.; Cadle, S.H.; Qian, T.Z. "Analysis of Remote Sensing Errors of Omissions and Commission Under FTP Conditions," *J. Air & Waste Manage. Assoc.* 1996, 46, 510.

2. Stephens, R.D.; Cadle, S.H. "Remote Sensing Measurements of Carbon Monoxide Emissions from On-road Vehicles," *J. Air & Waste Manage. Assoc.* 1991, 41, 39.

3. Davis, L.D.; DuBose, R.S.; Walden, T.; Rodgers, M.O. "Estimating I/M Program Effectiveness Through Analysis of I/M Records and Remote Sensing Results in Atlanta," The Emission Inventory: Programs and Progress, Air & Waste Manage. Association, Raleigh, NC, October 1995.

4. Fogelson, M.S.; Canon, M.B.; Grodzinsky, G.; DuBose, R.S.; Klochko, P.; Barker, T.; Rodgers, M.O. "Comparison of Remote Sensing Results from Different Cities with Centralized and Decentralized I/M Programs," In Proceedings of the AWMA/EPA Conference on Emissions Inventory: Durham, NC, October 1995.

5. User Guide and Description for Interim Remote Sensing Program Credit and Utility, Office of Mobile Sources, Ann Arbor, MI, EPA-420/R-96-004, September 1996.

6. Description and Documentation for Interim Vehicle Clean Screening, Office of Mobile Sources, Ann Arbor, MI, EPA-420/P-98-008, May 1998.

7. Stedman, D.H.; Bishop, G.A.; Zhang, Y.; Guenther, P.L. "Remote sensing of automobile emissions," in *Traffic Technology International '94*, UK & International Press, 1994, 194-198.

8. Peterson, J.E.; Stedman, D.H. "Find and fix the polluters, " *Chemtek* 1992, January 47.

9. Zhang, Y.; Stedman, D.H.; Bishop, G.A.; Beaton S.P.; Guenther, P.L.; McVey I.F. "Enhancement of Remote Sensing for Mobile Source Nitric Oxide," *J. Air & Waste Manage. Assoc.* 1996, 46, 25-29.

10. 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.

11. Woods, M. "Remote Emissions Testing Hits the Road," *Environmental Science and Technology,* Vol. 30, No. 6, 1996.

12. Heywood, J.B. *Internal Combustion Engine Fundamentals.* McGraw-Hill: New York, NY 1988, 62-99, 567-65.

13. Stedman, D.H.; Bishop, G.A.; Pitchford, M.L. Evaluation of a Remote Sensor for Mobile Source CO Emissions; Advanced Monitoring Division, Environmental Monitoring Systems Laboratory, Las Vegas, NV; EPA- 600/4-90-032 (NTIS PB91-148320), January 1991.

14. *Energy and Climate Change*, Report of the DOE Multi-Laboratory Climate Change Committee. Lewis Publishers: New York, NY, 1990, p.2.

15. *Energy and Climate Change*, Report of the DOE Multi-Laboratory Climate Change Committee. Lewis Publishers: New York, NY, 1990, p.32.