June 2003

Environmental Technology Verification Report

CLEAN AIR TECHNOLOGIES INTERNATIONAL, INC. REMOTE ON-BOARD EMISSIONS MONITOR

Prepared by
Battelle

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Environmental Technology Verification Report

ETV Advanced Monitoring Systems Center

CLEAN AIR TECHNOLOGIES INTERNATIONAL, INC. REMOTE ON-BOARD EMISSIONS MONITOR

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Notice

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the nation's air, water, and land resources. Under a mandate of national environmental laws, the Agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. To meet this mandate, the EPA's Office of Research and Development provides data and science support that can be used to solve environmental problems and to build the scientific knowledge base needed to manage our ecological resources wisely, to understand how pollutants affect our health, and to prevent or reduce environmental risks.

The Environmental Technology Verification (ETV) Program has been established by the EPA to verify the performance characteristics of innovative environmental technology across all media and to report this objective information to permitters, buyers, and users of the technology, thus substantially accelerating the entrance of new environmental technologies into the marketplace. Verification organizations oversee and report verification activities based on testing and quality assurance protocols developed with input from major stakeholders and customer groups associated with the technology area. ETV consists of seven environmental technology centers. Information about each of these centers can be found on the Internet at http://www.epa.gov/etv/.

Effective verifications of monitoring technologies are needed to assess environmental quality and to supply cost and performance data to select the most appropriate technology for that assessment. In 1997, through a competitive cooperative agreement, Battelle was awarded EPA funding and support to plan, coordinate, and conduct such verification tests for "Advanced Monitoring Systems for Air, Water, and Soil" and report the results to the community at large. Information concerning this specific environmental technology area can be found on the Internet at http://www.epa.gov/etv/centers/center1.html.

Acknowledgments

The authors wish to acknowledge the support of all those who helped plan and conduct the verification test, analyze the data, and prepare this report. In particular we would like to thank ETV stakeholders Jeff Cook, Clifford Glowacki, and Donald Stedman.

Contents

Page

Figures

Tables

List of Abbreviations

AMS	Advanced Monitoring Systems
ATL	Automotive Testing Lab
CL	chemiluminescence
CO	carbon monoxide
CO_2	carbon dioxide
CV	coefficient of variation
EPA	U.S. Environmental Protection Agency
ETV	Environmental Technology Verification
FID	flame ionization detector
FTP	federal test procedure
g	gram
GC	gas chromatography
HC	hydrocarbon
L	liter
LL	lower limit
mi	mile
NDIR	non-dispersive infrared
NIST	National Institute of Standards and Technology
NO_x	nitrogen oxides
O_2	oxygen
OBD	on-board diagnostic
OEM	on-board emissions monitor
PE	performance evaluation
QA/QC	quality assurance/quality control
QA	quality assurance
QMP	Quality Management Plan
REMOTE	real-world emissions monitoring on-board testing equipment
TSA	technical systems audit
UL	upper limit

Chapter 1
Background

The U.S. Environmental Protection Agency (EPA) supports the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized testing organizations; with stakeholder groups consisting of buyers, vendor organizations, and permitters; and with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance (QA) protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The EPA's National Exposure Research Laboratory and its verification organization partner, Battelle, operate the Advanced Monitoring Systems (AMS) Center under ETV. The AMS Center evaluated the performance of the Clean Air Technologies International Inc., REMOTE (Real-world Emissions Monitoring On-board Testing Equipment) on-board emissions monitor (OEM) in May of 2001. A delay by the vendor postponed the preparation of this verification report until early 2003.

Chapter 2
Technology Description

The objective of the ETV AMS Center is to verify the performance characteristics of environmental monitoring technologies for air, water, and soil. This verification report provides results for the verification testing of the Clean Air Technologies International, Inc., REMOTE OEM. Following is a description of the REMOTE OEM, based on information provided by the vendor. The information provided below was not verified in this test.

The REMOTE OEM is capable of measuring exhaust emissions from electronically controlled light-duty passenger vehicles and light trucks of model year 1996 and newer with on-board diagnostics (OBD) ports. The REMOTE OEM, using infrared techniques to measure carbon monoxide (CO), carbon dioxide (CO_2), and total hydrocarbons (HC) and electrochemical techniques to measure nitrogen oxides (NO_x), is designed to provide real-time on-road emissions measurements and to derive test- and bag-averaged emissions during standard vehicle test cycles, as used in vehicle dynamometer testing. The REMOTE OEM provides second-by-second total HC, CO, NO_x, CO_2, and oxygen (O_2) readings and total mass emissions summaries for individual test cycles. It includes a touch-screen computer and comes standard in a powder-coated aluminum housing.

Figure 2-1. Clean Air Technologies REMOTE On-Board Emissions Monitor

The REMOTE OEM is installed in the passenger seat of the vehicle and connects to the vehicle in three locations. The cigarette lighter provides the power in the majority of installations (auxiliary battery optional), the OBD port under the dashboard provides the engine data stream, and the sample exhaust probe is inserted into the tailpipe.

Chapter 3
Test Design and Procedures

3.1 Introduction

This verification test was conducted according to procedures specified in the AMS Center *Test/QA Plan for Verification of On-Board Vehicle Emission Monitors*.[1] The purpose of the test was to evaluate the performance of the Clean Air Technologies REMOTE OEM under realistic operating conditions.

The REMOTE OEM was tested in multiple vehicles to assess its overall accuracy (bias and precision) relative to emission measurements made by standard emission test equipment with a chassis dynamometer. The REMOTE OEM was also operated in on-road driving, to observe its performance under real-world conditions. Reliability and ease of use also were assessed.

3.2 Test Design

The verification test used the facilities of Automotive Testing Laboratory (ATL) in East Liberty, Ohio. For this test, three automatic-transmission, multi-port fuel injection, gasoline-powered test vehicles were rental cars obtained by the testing facility for both chassis dynamometer testing and road testing:

- Chevrolet Cavalier (1998, 2.2 L, 4 cylinder, 22,697 miles)
- Chevrolet Tahoe (1997, 5.7 L, 8 cylinder, 63,857 miles)
- Ford Taurus (1998, 3.0 L, 6 cylinder, 33,981 miles).

To establish intra-method precision (i.e., unit-to-unit relative error), duplicate REMOTE OEMs were operated side-by-side throughout all portions of the verification test.

In the first phase of the verification test, the duplicate REMOTE OEMs were operated on a vehicle running on a chassis dynamometer, and vehicle emissions were monitored by the REMOTE OEMs being verified and by standard emission testing equipment. Three dynamometer test runs were performed with each of the three vehicles on each of two test cycles: the Federal Test Procedure (FTP)[2] and the US06[2] cycle (Table 3-1). The FTP cycle consists of three segments, in each of which an integrated sample is collected in a gas sampling bag. The overall emissions from the cycle are based on all three bags. For the US06 cycle, one bag sample is collected over the duration of the cycle. These bag samples were analyzed using the emission testing equipment in place at ATL. The reference method emission results were compared with the

REMOTE OEM results on a second-by-second basis, on a test cycle basis for both the FTP and US06 cycles, and on a bag-by-bag basis for the FTP cycles.

Table 3-1. Summary of Chassis Dynamometer Test Cycles

Test cycle	Cavalier	Tahoe	Taurus	Total
FTP [(a)]	3	3	3	9
US06	3	3	3	9
Total	6	6	6	18

[(a)] Each FTP test cycle produced three bags, so 27 observations were obtained for the bag-level comparisons.

Three test cycles were conducted to provide information on test cycle-to-test cycle repeatability and to test whether interactions between vehicle type and test cycle have an impact on observed bias and precision. For example, levels of bias and/or precision may differ from vehicle to vehicle only during the FTP cycle, or one vehicle type may show consistent bias and precision during both test cycles, while the other two do not.

Following the chassis dynamometer test cycles summarized in Table 3-1, four additional US06 cycles were performed on the Cavalier. First, a single US06 cycle was performed with the Cavalier accessories (air conditioner, radio, lights, etc.) off, at each of three different temperatures (i.e., 30°F, 75°F, and 100°F). The fourth US06 cycle was performed at 100°F with the Cavalier's air conditioner operating at maximum capacity, to assess whether using vehicle accessories influences the performance of the REMOTE OEM.

For all of the test cycles, vehicle emissions were measured by the reference methods described in Section 3.3. These measurements were used to establish bias of the REMOTE OEM relative to the reference data. During each test cycle, vehicle emissions were monitored in real time by the reference methods and by the duplicate REMOTE OEMs for HC, CO, NO_x, and CO_2. Bias and REMOTE OEM precision were determined independently for HC, CO, NO_x, and CO_2.

In the second phase of the verification test, the duplicate REMOTE OEMs were installed in one of the test vehicles, and the vehicle was then driven over two routes for approximately 15 minutes each. The two routes consisted of one route that was predominantly stop-and-go traffic, and one that was predominantly sustained high-speed traffic. While the vehicle was driven over these two routes, second-by-second data were collected by the duplicate REMOTE OEMs. Results from the duplicate REMOTE OEMs were compared graphically to assess the unit-to-unit reproducibility of the OEM in on-road driving. The same on-road procedure was conducted using each of the three test vehicles.

3.3 Reference Methods

During the verification test, the following methods were implemented through the emission test equipment in the ATL facilities to measure the concentrations of HC, CO, NO_x, and CO_2 in vehicle emissions:

- HC—flame ionization detector (FID)
- CO—non-dispersive infrared spectroscopy (NDIR)
- NO_x—chemiluminescence (CL) analyzer
- CO_2—NDIR.

These methods are described in 40 CFR Part 86.[2] These methods served as the basis for evaluating the bias of the REMOTE OEM. These analyses were performed both in real time and on collected bag samples.

3.4 OEM Installation

The REMOTE OEMs were installed by a vendor representative, who ensured that each REMOTE OEM was calibrated and operating properly before testing began each day. The duplicate REMOTE OEMs were installed with appropriate plumbing to split the exhaust stream for analysis by both REMOTE OEMs. A leak check was performed before road testing and before each series of dynamometer runs to ensure the integrity of the exhaust sampling assembly. During the chassis dynamometer cycles, the vehicle battery was used to power one of the two REMOTE OEMs, and a secondary supply (independent of the vehicle battery) was used to power the other REMOTE OEM. During the on-road cycles, the duplicate OEMs were powered by the vehicle battery.

The installation activities (including on-site calibration, repairs, etc.) were documented by Battelle staff. Observations regarding installation time and simplicity, ease of use, practicality, passenger safety, etc., were based on the installation of a single unit.

3.5 Test Schedule

Testing was conducted between May 7 and May 10, 2001. Preparation of this verification report did not begin until early 2003 due to delays by the vendor. Chassis dynamometer test cycles were performed according to the schedule shown in Table 3-2 and were conducted with the vehicle accessories off, except where noted. Test cycle conditions were documented by the test facility in accordance with 40 CFR Part 86.[2] On-road tests were performed at the end of each testing day.

Because the test was not designed to determine emission rates for the test vehicles, strict adherence to the soak and preconditioning procedures described in 40 CFR Part 86[2] was not necessary. However, conditions were consistent for replicates of each test cycle. After the vehicle soak (12 to 36 hours), the test vehicle was placed on the dynamometer and prepared for testing.

Table 3-2. Schedule for Chassis Dynamometer Test Cycles

May 7, 2001	May 8, 2001	May 9, 2001	May 10, 2001
Cavalier - FTP	Tahoe - FTP	Tahoe - FTP	Cavalier - US06 @ 30°F
Cavalier - US06	Tahoe - US06	Tahoe - US06	Cavalier - US06 @ 75°F
Tahoe - FTP	Taurus - FTP	Taurus - FTP	Cavalier- US06 @ 100°F
Tahoe - US06	Taurus - US06	Taurus - US06	Cavalier - US06 @ 100°F w/AC
Taurus - FTP	Cavalier - FTP	Cavalier - FTP	
Taurus - US06	Cavalier - US06	Cavalier - US06	

Testing began with performance of an FTP cycle, followed within 10 minutes by a US06 cycle. Three FTP and three US06 cycles were thus performed at room temperature (75°F) alternately on the three test vehicles on each of three test days. On the fourth day of testing, a series of three US06 cycles were performed, including one at each of the following temperatures: 30°F, 75°F, and 100°F. These test cycles were conducted using the Cavalier, which had mid-range emissions among the three test vehicles as established by previous testing by the test facility. After this sequence of temperature tests, an additional US06 cycle was performed at 100°F with the Cavalier's air conditioner operating at maximum capacity. Figure 3-1 shows the Chevy Tahoe in the dynamometer cell during one of the test cycles. As shown in this figure, the two REMOTE OEMs were placed outside the vehicles in the chassis dynamometer cell for all test cycles.

Figure 3-1. Chevy Tahoe in Dynamometer Cell

For each test cycle, the exhaust emissions and engine activity data were monitored by both the reference emission test equipment and the duplicate REMOTE OEMs. The test facility recorded data on HC, CO, NO_x, and CO_2 emissions at the test, bag, and second-by-second level. Background concentrations of the target emissions were not measured. The second-by-second reference values were integrated over the periods of bag collection and compared with the corresponding bag values to assess agreement for the reference measurements of HC, CO, NO_x, and CO_2. Results of these comparisons are summarized in Section 4.1.

3.6 On-Road Testing

The three test vehicles used in the chassis dynamometer test cycles were driven on two separate routes over public roads while the duplicate REMOTE OEMs recorded second-by-second data for HC, CO, NO_x, and CO_2. Engine data were recorded by either of the REMOTE OEMs being tested. The vehicles began the on-road testing with a full tank of suitable, locally available, regular unleaded (87 octane) gasoline and completed the two driving routes in succession (i.e., on the same trip). The routes involved

- Approximately 15 minutes of stop-and-go traffic through a central business district
- Approximately 15 minutes of sustained high-speed driving on a freeway.

Test routes were consistent from vehicle to vehicle. An effort was made to conduct on-road testing under similar driving conditions (i.e., time of day, weather conditions). Figures 3-2 and 3-3 show external and internal views of the Chevy Tahoe before on-road testing.

Figure 3-2. External View of Chevy Tahoe Before On-Road Testing

Figure 3-3. View of the Duplicate REMOTE OEMs in the Chevy Tahoe Before On-Road Testing

Chapter 4
Quality Assurance/Quality Control

Quality assurance/quality control (QA/QC) procedures were performed in accordance with the quality management plan (QMP) for the AMS Center[3] and the test/QA plan for this verification test.[1]

4.1 Reference Method Calibrations and Checks

The dynamometer and laboratory instrumentation were calibrated by the ATL according to the standard operating procedures and schedules in place at the facility. These calibration specifications met or exceeded those described in 40 CFR Part 86.[2] Documentation of the calibrations was provided to Battelle by the ATL prior to test initiation.

Calibration verifications of specific instrumentation were performed at the request of Battelle during the verification test, and the results of the calibration verifications were provided to Battelle. In all cases the calibration verifications were within the specified tolerances, i.e., 5% for CO and CO_2, 10% for NO_x, and 15% for HC.

The second-by-second reference data were averaged over the collection periods of the bag samples in each test cycle, and the averaged data and bag analysis data were compared for consistency. All such comparisons showed agreement within the requisite criteria of 5% for CO and CO_2, 10% for NO_x, and 15% for HC.

4.2 Audits

4.2.1 Pre-Test Facility Audit

Two weeks prior to verification testing, the Battelle Quality Manager conducted an audit of the ATL to ensure that it had the equipment necessary to perform the verification test and that a satisfactory QA/QC program was implemented. The audit included a tour of the dynamometer facilities and a review of appropriate standard operating procedures and calibration records. The audit also included observations of ongoing dynamometer testing. There were no adverse findings as a result of this pre-test audit.

4.2.2 Performance Evaluation Audit

A performance evaluation (PE) audit was conducted to assess the quality of the reference measurements made in this verification test. This audit addressed only the emissions measurements provided by the reference methods. The audit was performed by analyzing National Institute of Standards and Technology (NIST)-traceable calibration gas standards that were independent of those used by the ATL during the testing. The acceptance criteria for the results of this audit were identical to those already in place at the ATL for calibration verification. The results of the performance audit are shown in Table 4-1, which indicates that all reference method readings were within 3% of those expected based on the PE standard concentrations.

Table 4-1. Results of Performance Audit

Audited Parameter	Acceptable Error	Actual Error	Passed Audit
HC	15%	2.8%	yes
CO	5%	-1.6%	yes
NO_x	10%	2.9%	yes
CO_2	5%	1.6%	yes

4.2.3 Technical Systems Audit

The Battelle Quality Manager conducted a technical systems audit (TSA) on May 8 and 9, 2001, to ensure that the verification test was performed in accordance with the test/QA plan,[1] reference methods, standard operating procedures used by the ATL, and the AMS Center QMP.[3] As part of the audit, the Battelle Quality Manager reviewed the reference methods used and compared actual test procedures to those specified in the test/QA plan, and reviewed data acquisition and handling procedures. Observations and findings from this audit were documented and submitted to the Battelle Verification Test Coordinator for response. No findings were documented that required any corrective action. The records concerning the TSA are permanently stored with the Battelle Quality Manager.

4.2.4 Audit of Data Quality

At least 10% of the data acquired during the verification test were audited. Battelle's Quality Manager traced the data from the initial acquisition, through reduction and statistical analysis, to final reporting, to ensure the integrity of the reported results. All calculations performed on the data undergoing the audit were checked.

4.3 QA/QC Reporting

Each assessment and audit was documented in accordance with the QMP in effect for the ETV AMS Center at the time of testing.[3] No adverse findings or potential problems were found. The results of the TSA were sent to the EPA.

4.4 Data Review

Records generated in the verification test received a one-over-one review within two weeks of generation before these records were used to calculate, evaluate, or report verification results. The review was performed by a Battelle technical staff member involved in the verification test, but not the staff member that originally generated the record. The person performing the review added his/her initials and the date to a hard copy of the record being reviewed.

Chapter 5
Statistical Methods

The statistical methods presented in this chapter were used to verify the performance factors noted in Section 3.1.

5.1 Bias

The bias of the REMOTE OEM was assessed for each emitted species at the test level based on the percent difference between the average concentration measurements or the grams/mile (g/mi) emission rates from the REMOTE OEM relative to the reference method. For each individual dynamometer run, the percent difference, d_i, between the REMOTE OEM and the reference measurement was calculated as

$$d_i = \frac{Y_i - X_i}{X_i} \times 100 \quad (1)$$

where Y_i represents the test level results from the REMOTE OEM and X_i represents the test level results of the reference method for a given emitted species. The average, D, and standard deviation, s, of these individual bias results were calculated from

$$D = \frac{\sum_{i=1}^{n} d_i}{n} \quad (2)$$

and

$$s = \sqrt{\frac{\left(\sum_{i=1}^{n} d_i^2\right) - \left(nD^2\right)}{n-1}} \quad (3)$$

where n is the total number of chassis dynamometer test cycles. The standard deviation and average difference were used to calculate the upper (UL) and lower (LL) 95% confidence limits for the bias of each REMOTE OEM according to

$$UL = D + t_{0.975}(s) \quad (4)$$

and

$$LL = D - t_{0.975}(s) \quad (5)$$

where $t_{0.975}$ is the 0.975 quantile of the Student's t distribution with n-1 degrees of freedom. Bias was calculated independently for each of the duplicate REMOTE OEMs and each emitted species. Additionally, bias was calculated independently for each vehicle and for each test cycle (i.e., FTP, US06). Note that, as the absolute measurement becomes small (Xi), the percent bias can become large since Xi is in the denominator.

5.2 Precision

Unit-to-unit precision was calculated based on the percent difference in the readings of the duplicate REMOTE OEMs relative to the mean of the readings, as shown below:

$$d_i^{'} = \frac{Y_i^{'} - Y_i}{(Y_i^{'} + Y_i)/2} \times 100 \tag{6}$$

where Y_i and $Y_i^{'}$ are the test level results for a given emitted species from the two duplicate REMOTE OEMs for each test cycle *i*. The coefficient of variation, CV_i, for each dynamometer test cycle and vehicle was calculated according to Equation (7).

$$CV_i = \left| \frac{d_i^{'}}{\sqrt{2}} \right| \tag{7}$$

The individual coefficients of variation for all test cycles and vehicles were pooled according to Equation (8) to determine the overall precision of the REMOTE OEM.

$$CV = \sqrt{\frac{\sum_{i=1}^{n} \left(CV_i\right)^2}{n}} \tag{8}$$

The UL and LL 90% confidence limits for the REMOTE OEM's CV are given by

$$UL = CV \sqrt{\frac{n}{\chi^2_{0.95,n}}} \tag{9}$$

and

$$LL = CV \sqrt{\frac{n}{\chi^2_{0.05,n}}} \tag{10}$$

where *n* is the number of degrees of freedom, and $\chi^2_{0.95,n}$ and $\chi^2_{0.05,n}$ are the 0.95 and 0.05 quantiles, respectively, of the χ^2 distribution with *n* degrees of freedom. Precision was assessed independently for each emitted species, as well as for each vehicle and each test cycle.

Supplemental comparisons were made at the second-by-second level to determine the instantaneous unit-to-unit reproducibility of the duplicate REMOTE OEMs. As with the test level results, these comparisons were made based on a percent difference calculation.

5.3 Other Factors

Second-by-second data from the OBD port and the REMOTE OEM were compared graphically for the Ford Taurus to illustrate temporal correlations between the vehicle operational parameters and the measured concentrations of the emitted species in the vehicle exhaust. Likewise, second-by-second data from the reference monitors were compared visually against those from the REMOTE OEM to illustrate temporal correlations. No statistical evaluations were made of these second-by-second comparisons because of differences in the lag times and response times between the reference monitors and the REMOTE OEM. For the on-road testing, second-by-second comparisons were made between the results of the duplicate REMOTE OEMs. Finally, a linear regression comparison was made between the REMOTE OEM and the reference measurements.

Chapter 6
Test Results

Two types of data were recorded during this verification test. The first type consisted of second-by-second data that recorded HC, CO, NO_x, and CO_2 emission levels. The second type of data were the integrated sample results from collected bag concentrations during the FTP and US06 cycles. In this case, the emissions from the vehicle were integrated by collection over a time period of several minutes, and the concentrations of HC, CO, NO_x, and CO_2 in the collected bag samples were measured at the end of the collection period with the reference monitors. The REMOTE OEM did not measure this concentration directly, but rather performed a numeric integration over the same period to calculate a corresponding bag or integrated sample concentration value. Figures 6-1a-d show the comparisons of the test cycle sample data for the reference monitors and the corresponding integrated data from the two REMOTE OEMs (A and B) for each of the test cycles in the order they were conducted. Figures 6-1a-d show results for HC, CO, NO_x, and CO_2, respectively. All data in these figures are in terms of grams-per-mile (g/mi) emissions of the indicated species.

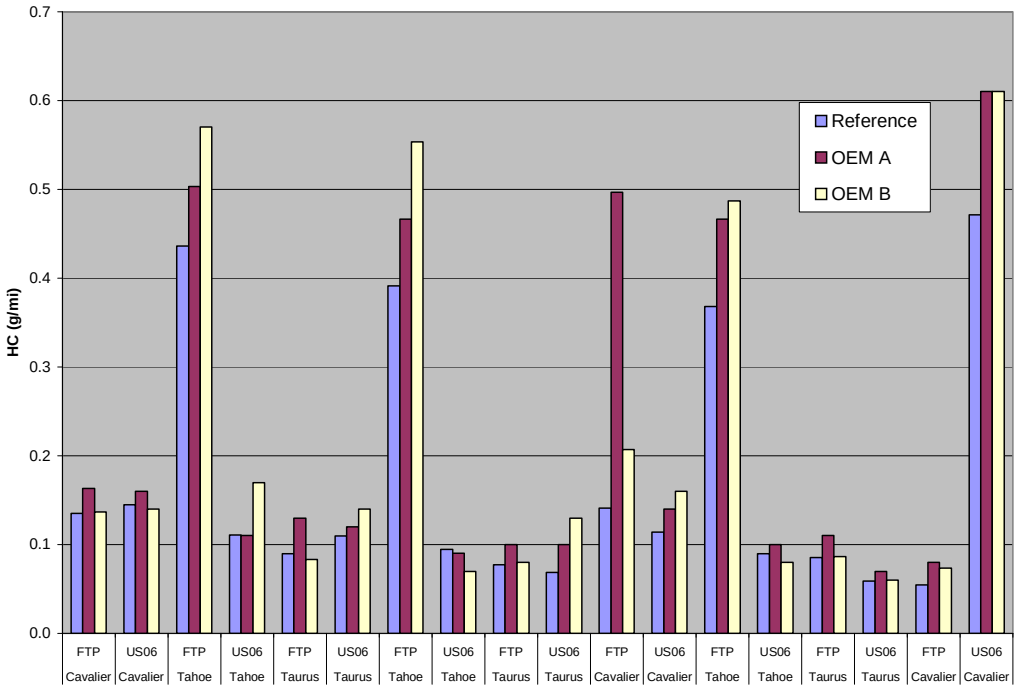

Figure 6-1a. Integrated Sample Comparison for Hydrocarbons

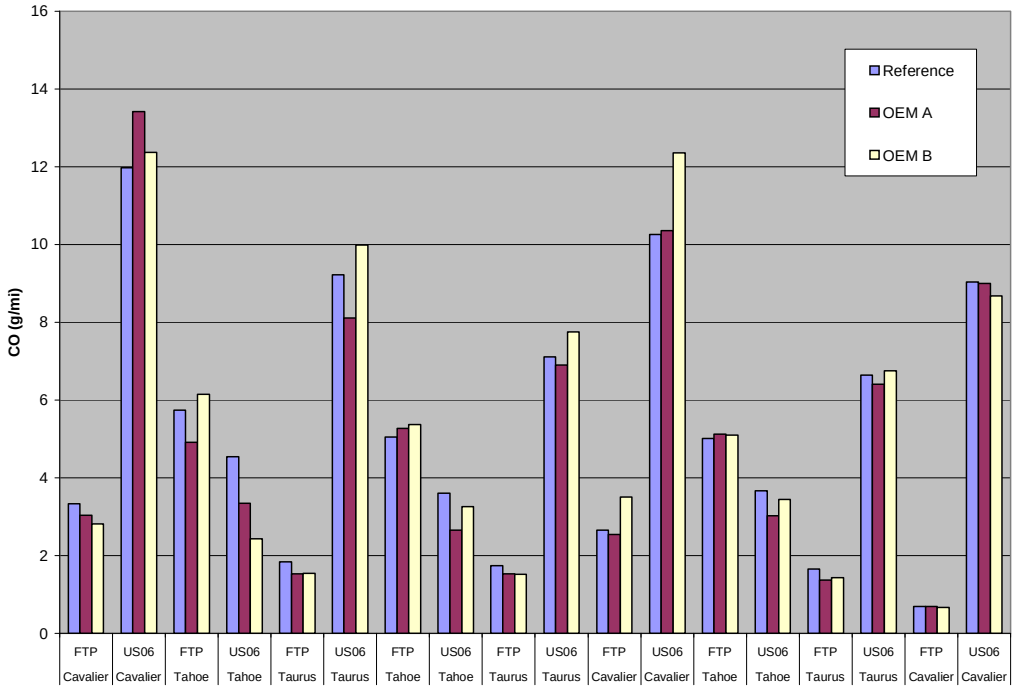

Figure 6-1b. Integrated Sample Comparison for Carbon Monoxide

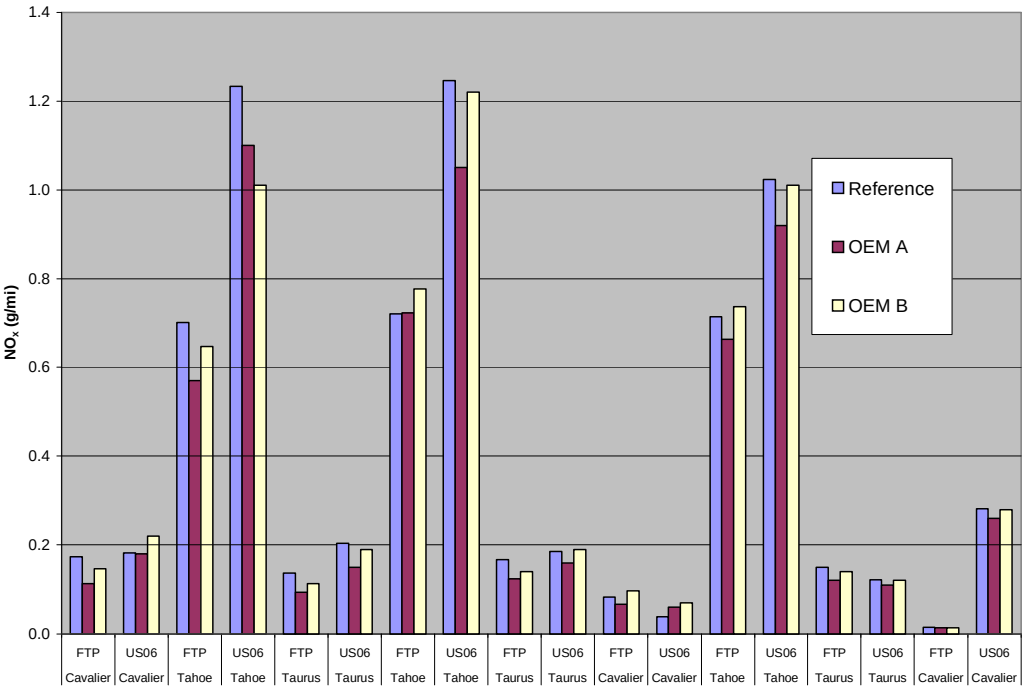

Figure 6-1c. Integrated Sample Comparison for Nitrogen Oxides

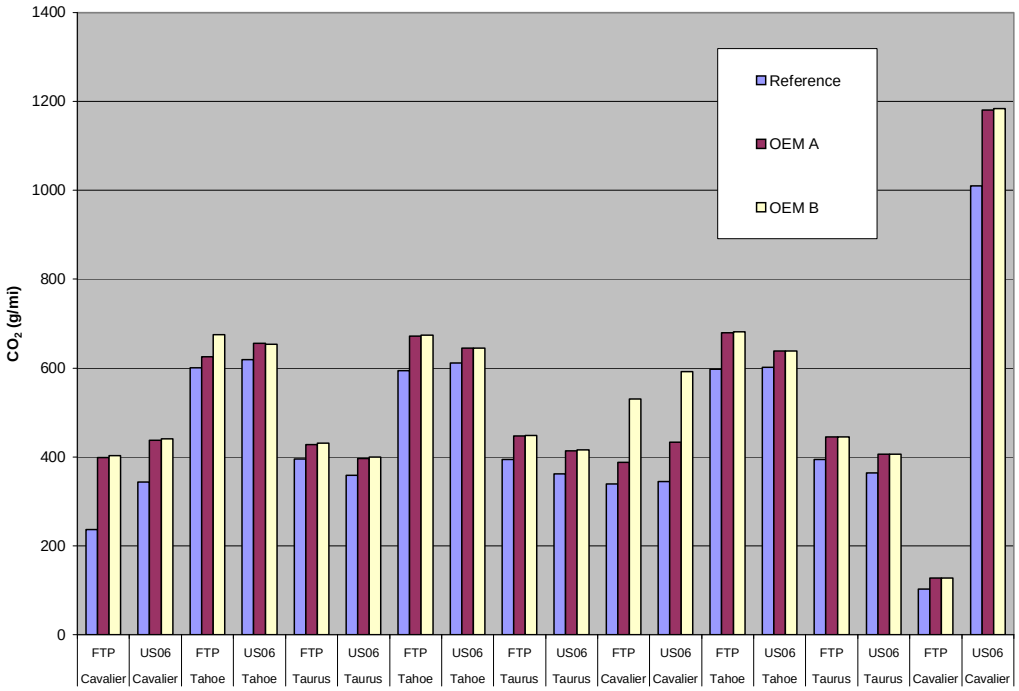

Figure 6-1d. Integrated Sample Comparison for Carbon Dioxide

It can be seen from these figures that the results from the duplicate REMOTE OEMs generally agreed with one another and also showed agreement with the reference results in most cases.

During each FTP cycle, three individual bags were collected in succession. The bag-by-bag FTP sample data from the reference measurements and the corresponding integrated data from the two REMOTE OEMs (A and B) are shown in Figures 6-2a-d, in the order they were collected. Figures 6-2a-d show results for HC, CO, NO_x, and CO_2, respectively. These figures again illustrate the general agreement between the duplicate REMOTE OEMs, and the comparison with reference results from the individual bags collected during different FTP cycles.

6.1 Bias

Bias results were calculated according to Equations (1-5) in Section 5.1. These bias results express the average percent difference between the REMOTE OEM results and the reference results. This calculation was performed for the integrated sample data for the entire test, and also separately for each vehicle and each test cycle (FTP and US06). Table 6-1 shows the results of these calculations. For the overall verification test, the smallest relative bias is found for OEM B measuring NO_x, at 1.96 ± 3.90%, and the largest is found for OEM A while measuring HC, at 34.8 ± 9.56%. Considering the bias results organized by test vehicle and test cycle, in general, both REMOTE OEMs exhibited smaller percent biases while measuring NO_x and CO, ranging

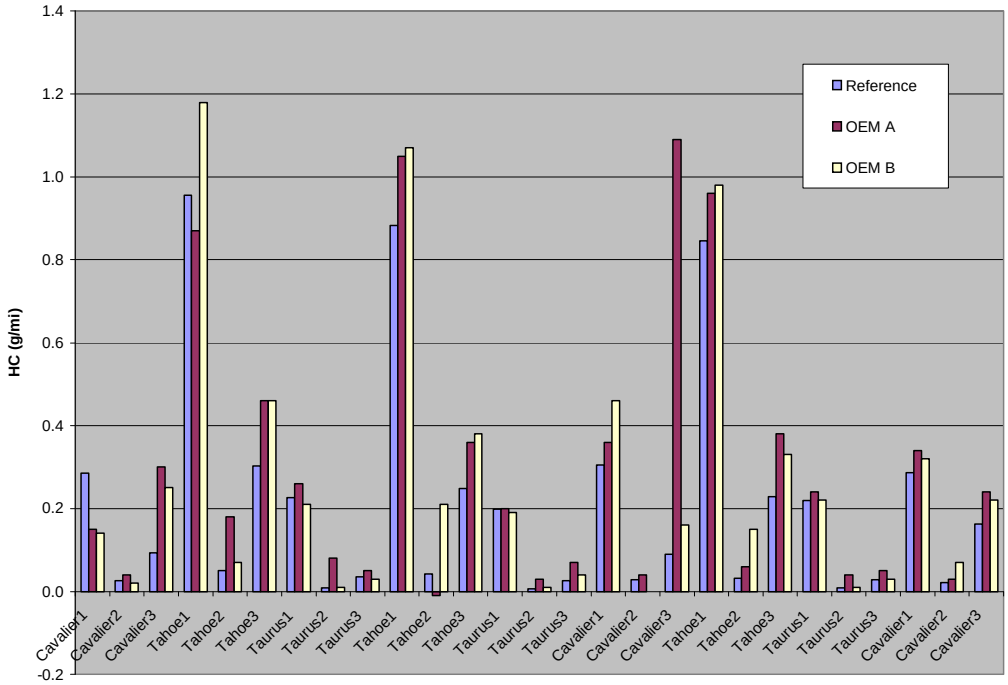

Figure 6-2a. FTP Individual Bag Comparison for Hydrocarbons

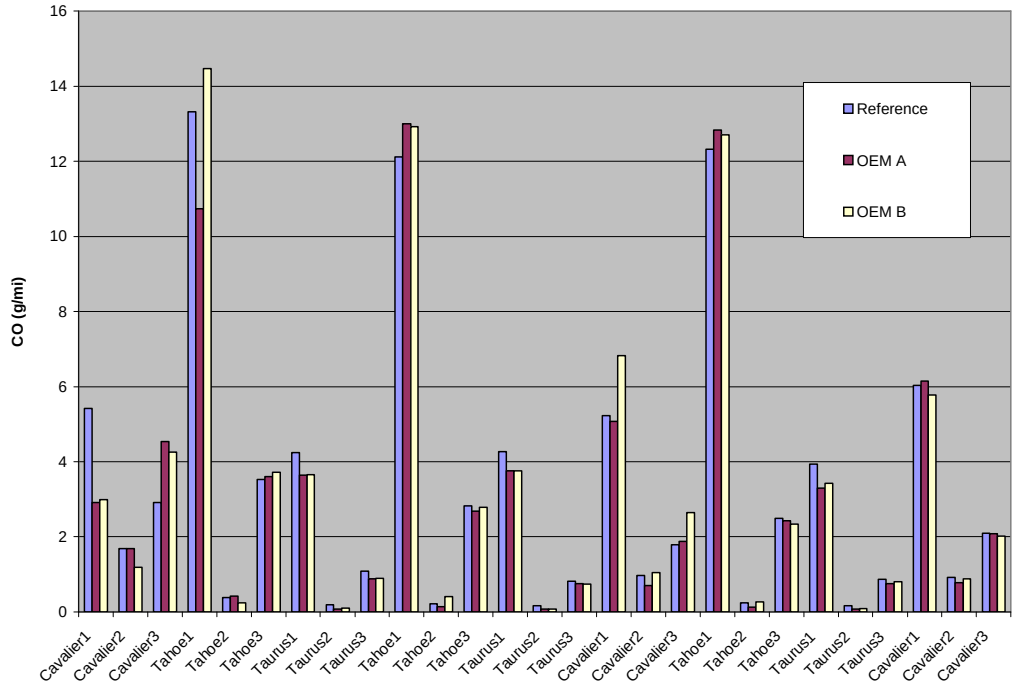

Figure 6-2b. FTP Individual Bag Comparison for Carbon Monoxide

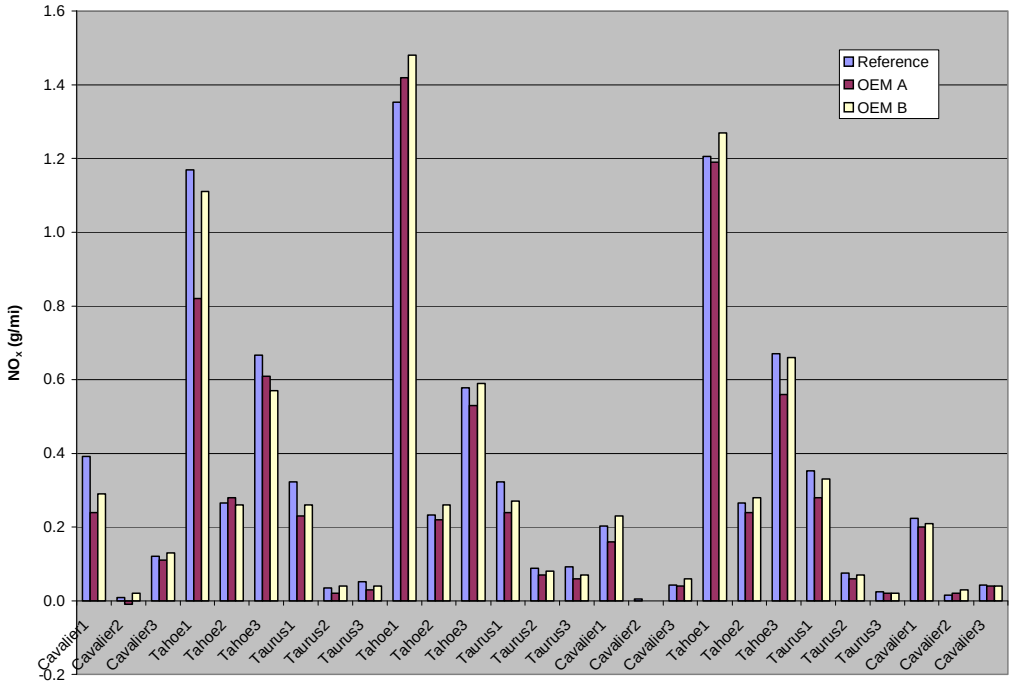

Figure 6-2c. FTP Individual Bag Comparison for Nitrogen Oxides

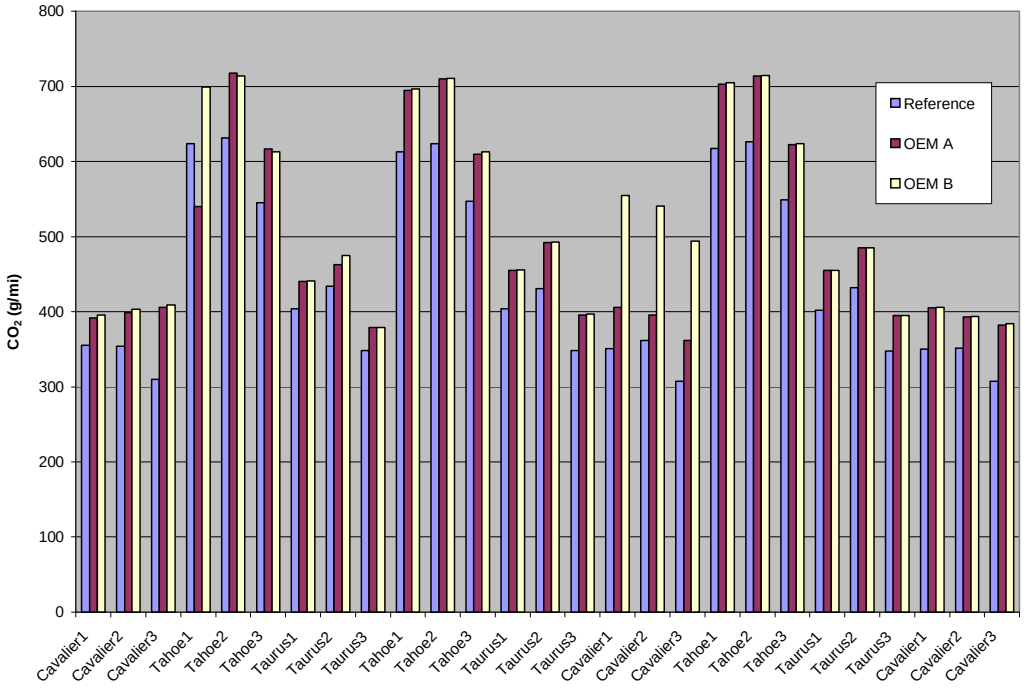

Figure 6-2d. FTP Individual Bag Comparison for Carbon Dioxide

Table 6-1. Percent Bias Values and Confidence Intervals for REMOTE OEM

Bias Pooling	OEM A				OEM B			
	HC	CO	NO_x	CO_2	HC	CO	NO_x	CO_2
Total Test								
% Bias	34.8	-7.95	-11.2	16.5	21.5	-2.07	1.96	22.2
±	9.56	1.80	3.35	2.50	4.82	2.84	3.90	3.60
Cavalier								
% Bias	**63.9**	**-0.14**	**-1.93**	**29.5**	**24.9**	**5.40**	**16.5**	**44.7**
±	**15.8**	**1.19**	**5.33**	**3.39**	**3.56**	**2.98**	**6.01**	**4.11**
Tahoe								
% Bias	**11.2**	**-12.9**	**-10.3**	**8.09**	**20.1**	**-7.79**	**-3.04**	**9.53**
±	**2.22**	**2.09**	**1.46**	**0.73**	**4.97**	**3.12**	**1.64**	**0.70**
Taurus								
% Bias	**29.4**	**-10.8**	**-21.3**	**11.8**	**19.4**	**-3.80**	**-7.58**	**12.3**
±	**2.42**	**1.05**	**1.42**	**0.39**	**6.12**	**1.94**	**1.32**	**0.34**
FTP cycles								
% Bias	53.9	-7.47	-18.1	19.2	20.6	-1.56	-4.57	25.2
±	12.8	1.40	2.05	3.29	3.48	2.63	1.98	3.78
US06 cycles								
% Bias	15.8	-8.42	-4.23	13.7	22.4	-2.57	8.48	19.2
±	2.62	2.22	4.07	1.39	6.11	3.19	5.06	3.57

Note: Bold rows show results by vehicle.

between -0.14 and 21.3% for OEM A and between -1.56 and 16.5% for OEM B. Larger percent biases were found while measuring HC and CO_2, ranging between 8.09 and 63.9% for OEM A and between 9.53 and 44.7% for OEM B. There was no consistent trend in OEM bias relative to the identity of the test vehicle or the test cycle.

6.2 Unit-to-Unit Precision

To calculate the unit-to-unit precision of the OEM, a CV was determined for each dynamometer test cycle by vehicle and by test cycle. Table 6-2 shows the results of these calculations.

Unit-to-unit precision was measured by the pooled CVs of results from the duplicate OEMs. In nearly all cases, the CVs for all the emitted species from all the vehicles were less than 5%. The largest CV was reported for HC during the Cavalier test, at 8.97 ± 11.6% over a tested range of 0.05 to 0.47 (g/mi) (Figure 6-1a). The smallest CV was seen for CO during the Cavalier test, at 1.11 ± 1.43% over a tested range of 0.70 to 12.0 (g/mi) (Figure 6-1b).

Table 6-2. Unit-to-Unit Precision Results and Confidence Intervals for REMOTE OEM

Precision Pooling	HC	CO	NO_x	CO_2
Total Test				
% CV	6.04	2.54	4.03	3.17
±	2.66	1.12	1.78	1.40
Cavalier				
% CV	8.97	1.11	4.73	4.89
±	11.6	1.43	6.10	6.30
Taurus				
% CV	4.77	2.32	4.59	1.99
±	6.15	2.99	5.92	2.57
Tahoe				
% CV	2.50	3.57	2.29	1.50
±	3.23	4.60	2.96	1.93
FTP Cycles				
% CV	7.90	2.05	4.4	3.71
±	6.44	1.67	3.58	3.02
US06 Cycles				
% CV	4.77	2.32	4.59	1.99
±	2.65	2.40	2.95	2.05

6.3 Other Factors

6.3.1 Reliability and Ease of Use

All data were collected as expected, and the REMOTE OEMs had no downtime during the tests. The REMOTE OEMs were installed in the vehicles for on-road testing with no difficulty. Installation time for a single unit was between 5 and 15 minutes for the on-road portion of the verification test. No repairs of either of the two OEMs were required during the verification test. Operation at 30°F and at 100°F had no adverse impact on OEM reliability, and operation over this range showed no consistent effect of temperature on OEM bias for any of the measured species.

6.3.2 Other Unit-to-Reference Method Comparisons

Figures 6-3a-d show the second-by-second data from the reference method and REMOTE OEMs in the May 9, 2001, FTP cycle with the Ford Taurus. Due to its mid-range engine size, the data from the Ford Taurus are presented. These data show a graphical representation of speed of response and agreement between the two OEMs and the reference methods. No statistical calculations were performed using these data. However, the data illustrate the temporal correlations between the REMOTE OEMs and the reference methods. These figures show general agreement between the reference monitors and the two REMOTE OEMs on the timing and level of vehicle emissions. There was some time delay between the reference monitors and the REMOTE OEMs, and some difference in the height of transient peaks, due to the different lag times in sampling by the reference monitors. Data from on-road testing with the two OEM units showed very similar agreement to the FTP second-by-second data shown in Figures 6-3a-d.

Linear regression comparisons of the REMOTE OEM results with FTP bag results are presented graphically in Figures 6-4a-d for each of the chassis dynamometer test cycles. These figures are based on the bag sample data presented above in Figures 6-2a-d, i.e., n=27 for each linear regression shown.

The linear regression results show that, except for the OEM A HC results (r^2 of 0.54) (Figure 6-4a), both OEM A and OEM B had coefficients of determination greater than 0.86 for all four emitted species measured. The slopes of the linear regressions for OEM A and OEM B relative to FTP bag results were between 0.97 and 1.03 for CO_2 over a tested range of 300 to 620 (g/mi). The slopes were between 0.95 and 1.05 for CO over a tested range of 0 to 13 (g/mi) and between 0.92 and 1.03 for NO_x over a tested range of 0 to 1.4 (g/mi). However, the slopes of the linear regressions for OEM A and OEM B were between 0.62 and 0.79 for HC over a tested range of 0 to 1 (g/mi). The HC results may be because of the different analytical techniques used (i.e., infrared absorption in the OEM measurements, FID in the reference measurements).

6.3.3 Temperature Effect

The results from the tests conducted at different cabin temperatures are shown in Table 6-3 as percent bias relative to the reference measurements. The results from these tests indicate that, while sometimes large differences occurred between the reference and OEM measurements, these differences were not consistently greater at elevated (100°F) or reduced (30°F) temperatures, relative to the 75°F condition. The largest bias values (88.6 to 96.9%) occurred for NO_x with both OEM units at the 100°F condition. It is noteworthy that these biases had an opposite sign in the two tests at 100°F, i.e., -96.9% in the third test and +88.6% in the fourth test (Table 6-3). The OEM experienced no observable malfunctions due to the changing testing temperatures.

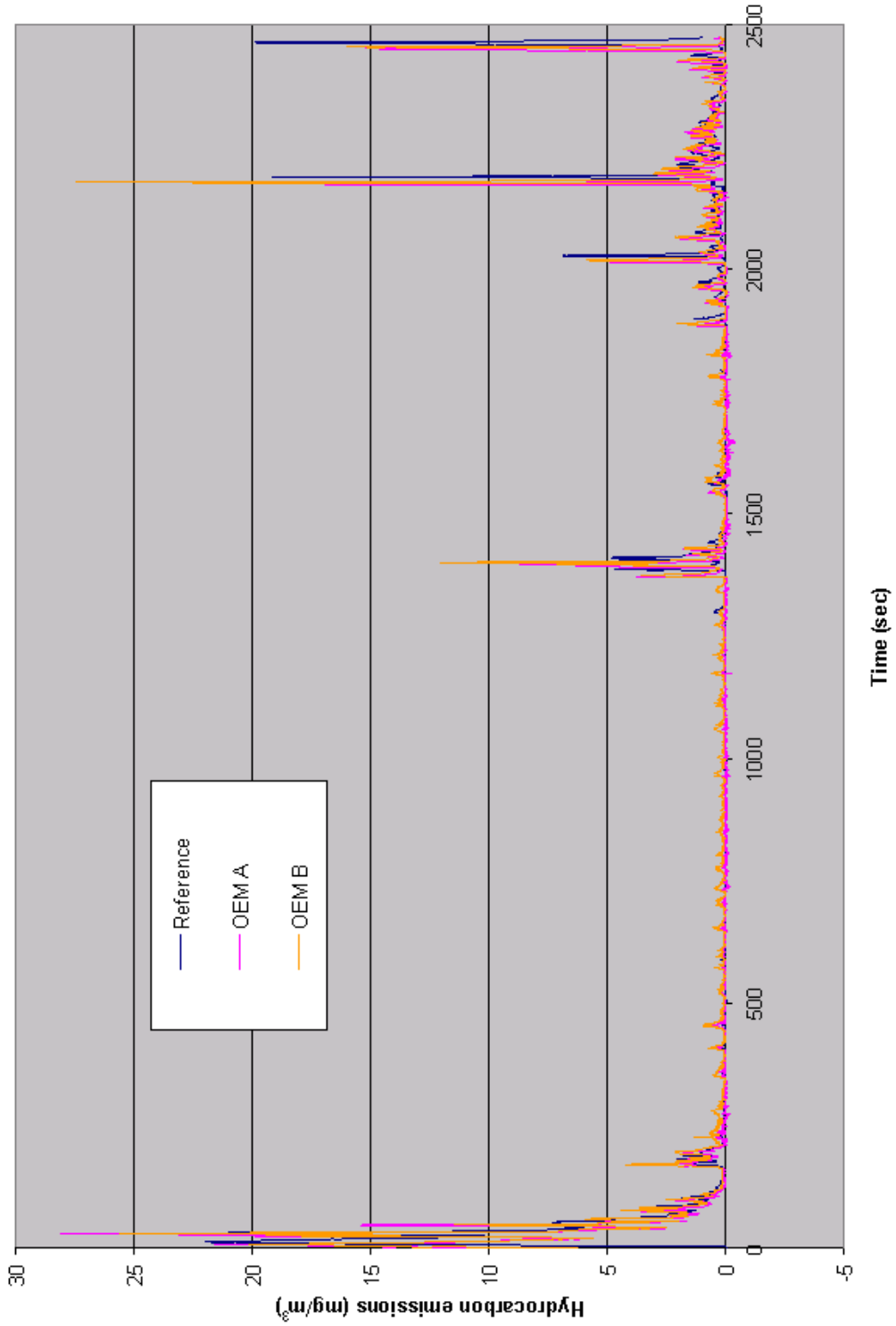

Figure 6-3a. Second-by-Second from Duplicate REMOTE OEMs and the Reference Method for Hydrocarbons During an FTP Cycle

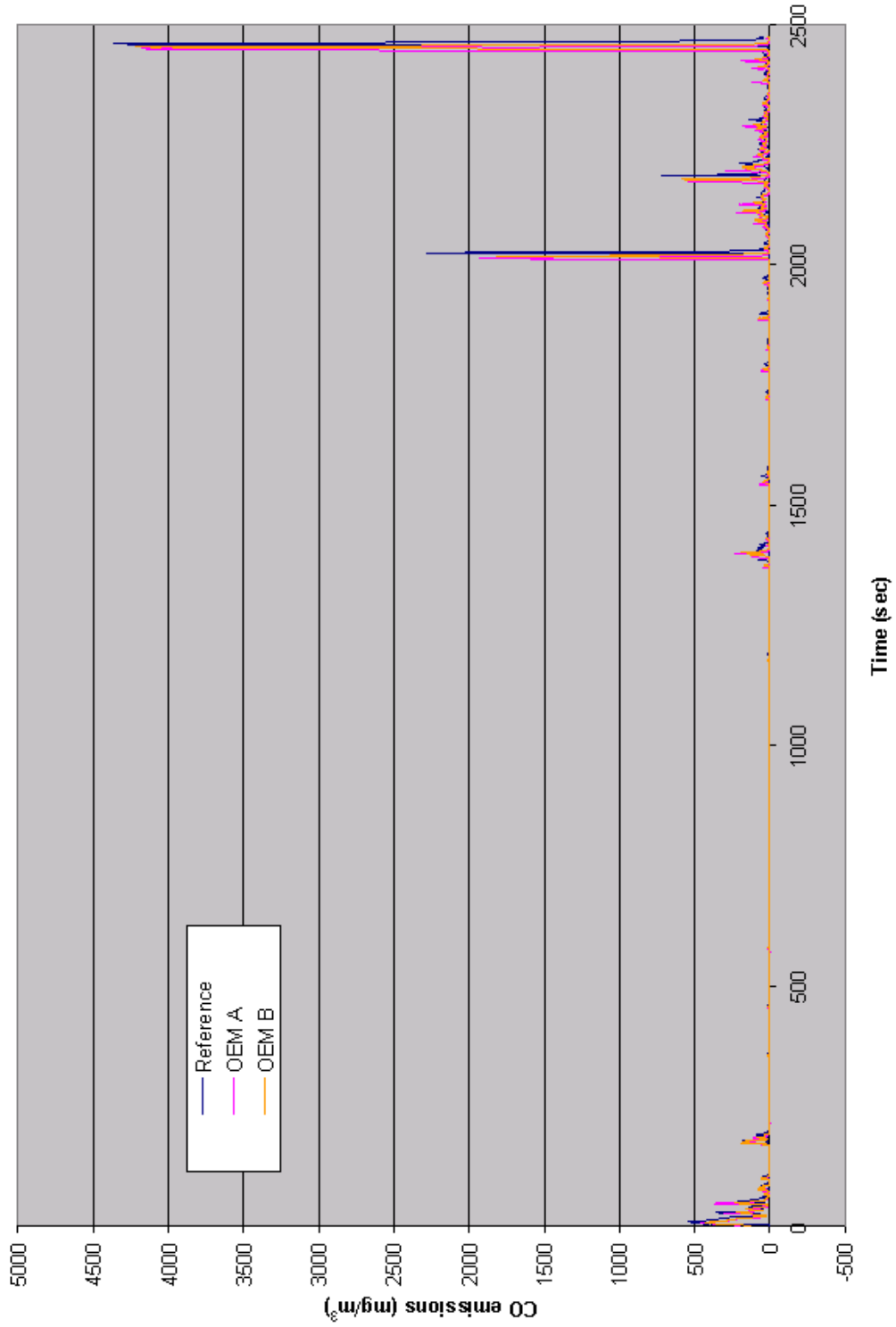

Figure 6-3b. Second-by-Second Data from Duplicate REMOTE OEMs and the Reference Method for Carbon Monoxide During an FTP Cycle

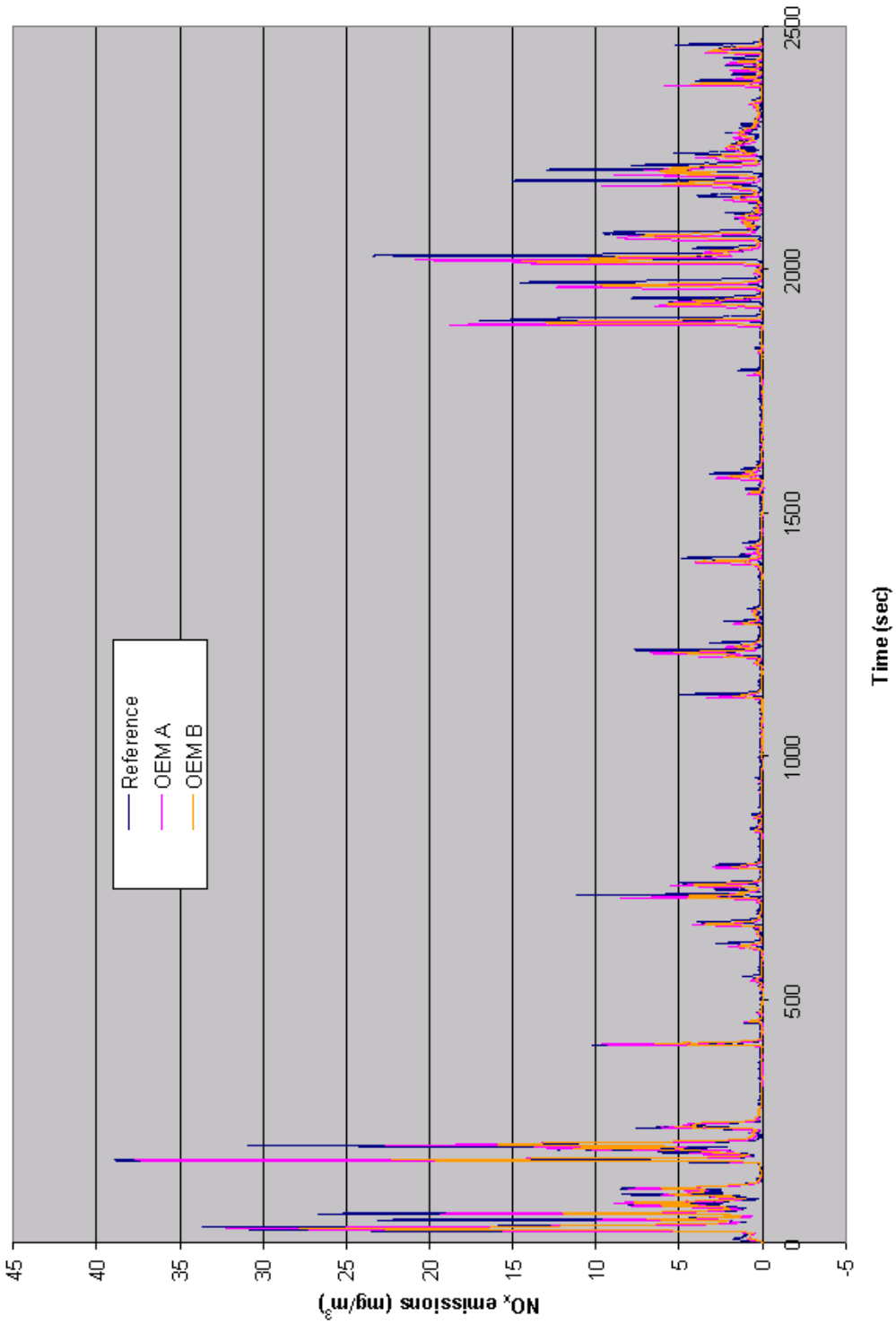

Figure 6-3c. Second-by-Second Data from Duplicate REMOTE OEMs and the Reference Method for Nitrogen Oxides During an FTP Cycle

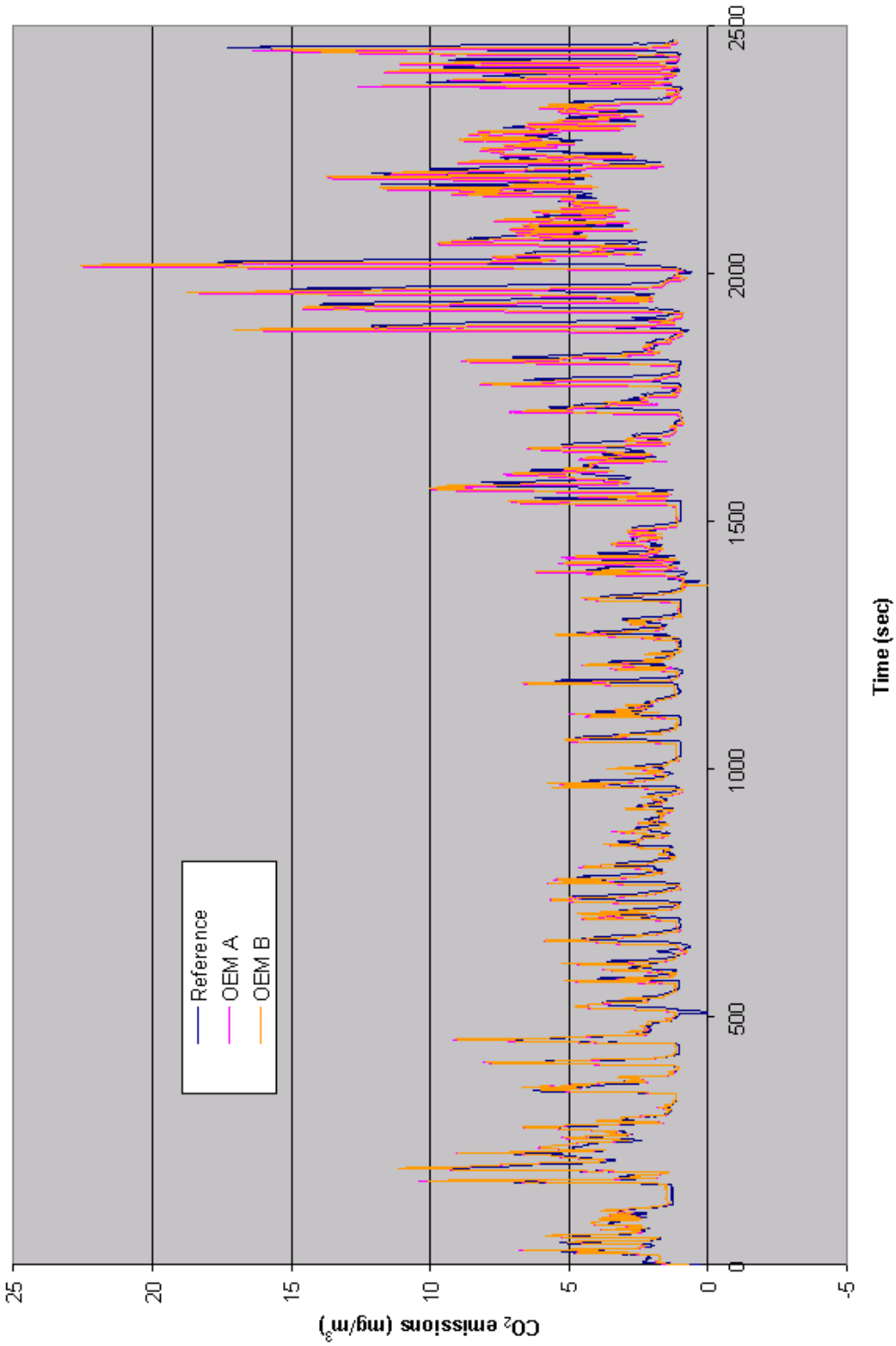

Figure 6-3d. Second-by-Second Data from Duplicate REMOTE OEMs and the Reference Method for Carbon Dioxide During an FTP Cycle

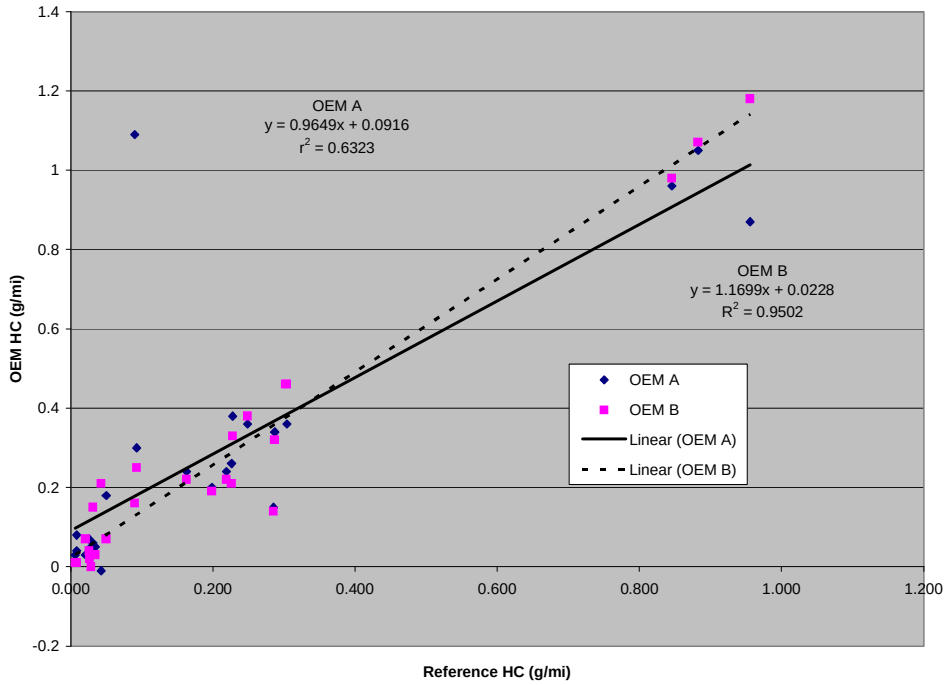

Figure 6-4a. Linear Regression Comparison Between Reference Method and REMOTE OEM for Hydrocarbons

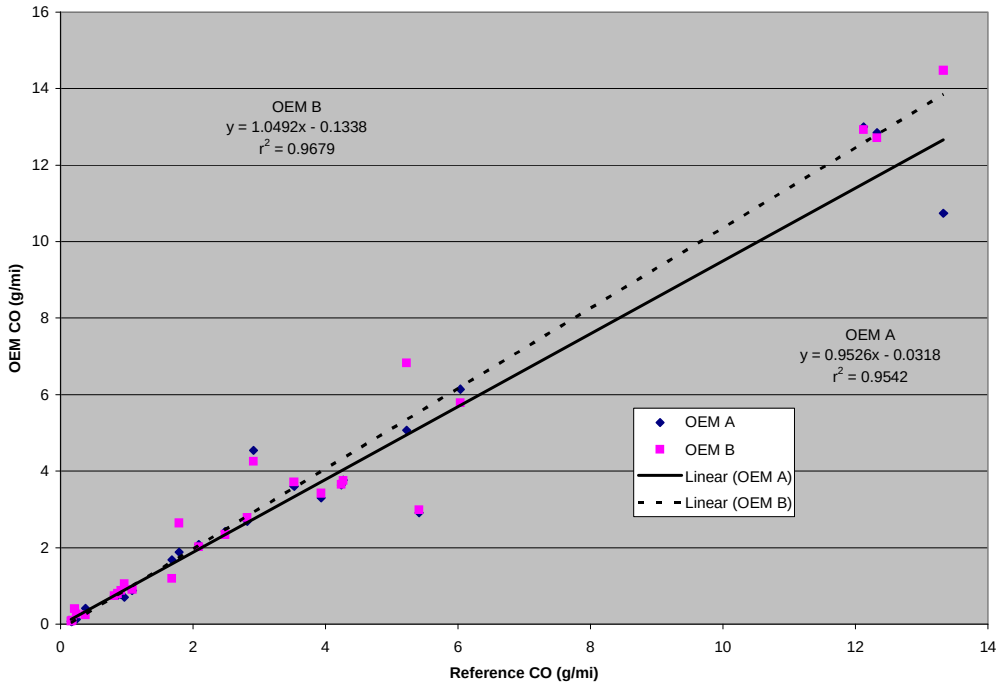

Figure 6-4b. Linear Regression Comparison Between Reference Method and REMOTE OEM for Carbon Monoxide

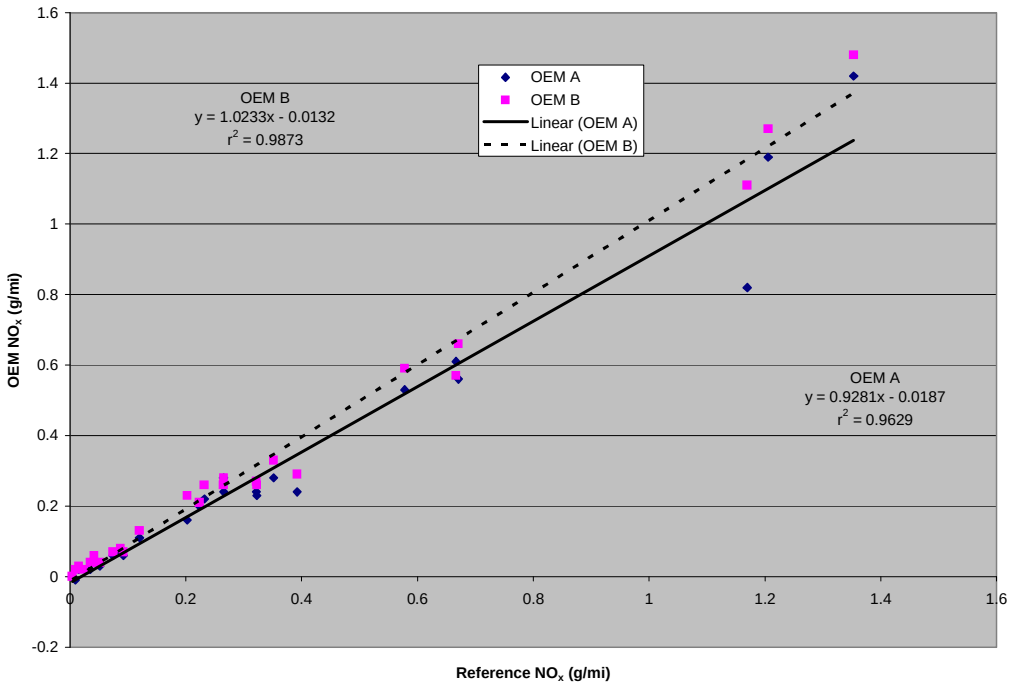

Figure 6-4c. Linear Regression Comparison Between Reference Method and REMOTE OEM for Nitrogen Oxides

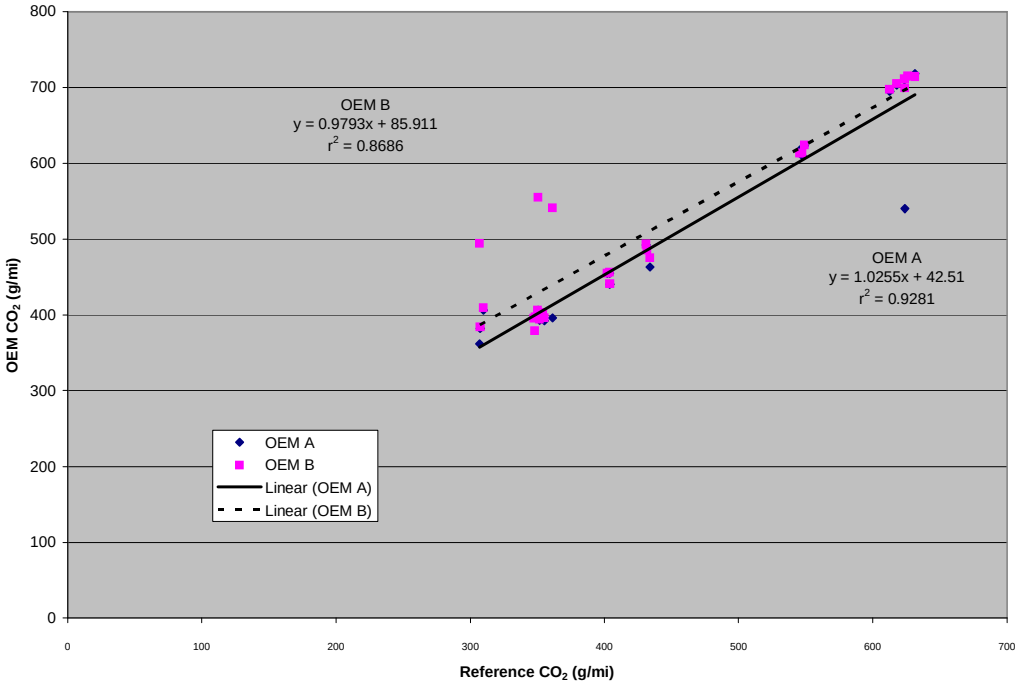

Figure 6-4d. Linear Regression Comparison Between Reference Method and REMOTE OEM for Carbon Dioxide

Table 6-3. Temperature Effect Results (US06 Cycles)

	% Bias							
	OEM A				OEM B			
Condition	HC	CO	NO_x	CO_2	HC	CO	NO_x	CO_2
30°F, Accessories Off	47.1	19.9	-7.46	-18.6	-16.4	1.49	-7.46	-19.2
75°F, Accessories Off	22.4	7.97	-0.23	-22.5	-32.0	-4.27	-50.3	-23.3
100°F, Accessories Off	-21.9	4.64	-96.9	-19.4	-60.4	-7.64	-96.9	-19.4
100°F; AC Max, Hot	-29.3	-15.7	88.6	-16.0	-70.1	-30.6	88.6	-16.0

Chapter 7
Performance Summary

Duplicate REMOTE OEMs were tested for bias and unit-to-unit precision in FTP and US06 dynamometer test cycles with three vehicles. Considering all tests with all vehicles, OEM B had the smallest relative bias, for NO_x, at 1.96 ± 3.90%, and OEM A had the largest, for HC, at 34.8 ± 9.56%. Considering the test results organized by test vehicle and test cycle, both OEMs A and B exhibited smaller percent biases for NO_x and CO, ranging between -0.14 and 21.3% for OEM A and between 1.56 and 16.5% for OEM B. Both OEMs A and B exhibited larger percent biases for HC and CO_2, ranging between 8.09 and 63.9% for OEM A and between 9.53 and 44.7% for OEM B.

Unit-to-unit precision was measured by the pooled CVs of results from the duplicate OEMs. In nearly all cases, the CVs of the duplicate OEMs for all the emitted species with all the vehicles were less than 5%. The largest CV was reported for HC during the Cavalier test, at 8.97 ± 11.6% over a tested range of 0.05 to 0.47 (g/mi). The smallest CV was seen for CO during the Cavalier test, at 1.11 ± 1.43% over a tested range of 0.70 to 12.0 (g/mi).

In assessing reliability and ease of use, all data were collected as expected, and the monitors had no downtime during the tests. The REMOTE OEMs were installed in the vehicles for on-road testing with no difficulty. Operation at 30°F and at 100°F had no adverse impact on OEM reliability, and operation over this range did not show a consistent effect of temperature on OEM bias for any of the measured species.

The second-by-second data for the reference method and the REMOTE OEMs illustrate close agreement. A time delay between the reference monitors and the REMOTE OEMs was due to the different lag times in sampling by the reference monitors.

The linear regression of averaged OEM results against FTP bag results shows that, except for the OEM A HC results (r^2 of 0.54), both OEM A and OEM B had coefficients of determination greater than 0.86 for all four emitted species. The slopes of the linear regressions for OEM A and OEM B were between 0.97 and 1.03 for CO_2 over a tested range of 300 to 620 (g/mi). The slopes were between 0.95 and 1.05 for CO over a tested range of 0 to 13 (g/mi) and between 0.92 and 1.03 for NO_x over a tested range of 0 to 1.4 (g/mi). However, the slopes of the linear regressions for OEM A and OEM B were between 0.62 and 0.79 for HC over a tested range of 0 to 1 (g/mi). The HC results may be because of the different analytical techniques used (i.e., infrared absorption in the OEM measurements, FID in the reference measurements).

Chapter 8
References

1. *Test/QA Plan for Verification of On-Board Vehicle Emissions Monitors*, Battelle, Columbus, Ohio, April 26, 2001.

2. U.S. Environmental Protection Agency, "Control of Air Pollution from New and In-Use Motor Vehicles and New and In-Use Motor Vehicle Engines: Certification and Test Procedures," 40 CFR Part 86.

3. *Quality Management Plan (QMP) for the ETV Advanced Monitoring Systems Pilot*, Version 2.0, U.S. EPA Environmental Technology Verification Program, Battelle, Columbus, Ohio, October 2000.