SRI/USEPA-GHG-VR-05
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Environmental Technology Verification Report

ANR Pipeline Company Parametric Emissions Monitoring System (PEMS)

Prepared by

Southern Research Institute

Under a Cooperative Agreement With
U.S. Environmental Protection Agency

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Greenhouse Gas Technology Verification Center

A U.S. EPA Sponsored Environmental Technology Verification Organization

ANR Pipeline Company
Parametric Emissions Monitoring System (PEMS)

Technology Verification Report

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Under EPA Cooperative Agreement CR 826311-01-0

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The Greenhouse Gas Technology Verification Center wishes to thank the staff and employees of Coastal Corporation and its member company, ANR Pipeline Company, for their invaluable service in hosting this test. They provided the compressor station to test this technology, and gave technical support during the setup and field testing of the PEMS technology. Key ANR personnel who should be recognized for contributing to the success of the testing include Curtis Pedersen, Joseph Weisbrod, Michael Scudder, Ron Bickel, Mike Haller, Jeff Beach, and George Jirkos. Special thanks are also extended to the Center's Oil and Natural Gas Industry Stakeholder Group for reviewing this report.

1.0 INTRODUCTION

1.1 BACKGROUND

The U.S. Environmental Protection Agency's Office of Research and Development (EPA-ORD) has created a program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of the Environmental Technology Verification (ETV) program is to further environmental protection by substantially accelerating the acceptance and use of improved and more cost-effective technologies. The ETV program is funded by the U.S. Congress in response to the belief that there are many viable environmental technologies that are not being used because of the lack of credible third-party performance testing. With performance data developed under this program, technology buyers and permitters in the United States and abroad will be better equipped to make informed decisions regarding environmental technology purchases.

The Greenhouse Gas Technology Verification Center (the Center) is one of 12 independent verification organizations operating under the ETV program. The Center is managed by EPA's partner verification organization, Southern Research Institute (SRI). The Center provides a verification testing capability to greenhouse gas (GHG) technology vendors, buyers, exporters, and others who have a need for independent performance data. This process consists of developing verification protocols, conducting field tests, collecting and interpreting field and other data, and reporting findings. Performance evaluations are conducted according to externally reviewed test plans and established protocols for quality assurance.

The Center is guided by volunteer groups of Stakeholders. These Stakeholders offer advice on technology areas and specific technologies most appropriate for testing, help disseminate results, and review test plans and verification reports. The Center's Executive Stakeholder Group consists of national and international experts in the area of GHG Technology, and verification. It includes representatives from industry trade organizations, environmental technology finance groups, and various government organizations. The Executive Group helps select technology areas that the Center should focus on. Oil and gas industry technology areas were targeted by the Executive Stakeholder Group as showing promise for independent testing.

To pursue verification testing in the oil and gas industries, the Center has established an Oil and Gas Industry Stakeholder Group. The group consists of representatives from production, transmission, and storage sectors, technology manufacturers, and environmental regulatory groups. Individuals who are members of the Oil and Gas Industry Stakeholder Group have voiced support for the Center's mission, identified a need for independent third-party verification, prioritized specific technologies for testing, and identified verification test parameters that are most valuable to their industry.

In the natural gas industry, interstate gas pipeline operators use large gas-fired engines to provide the mechanical energy needed to drive pipeline gas compressors. A parametric emissions monitoring system (PEMS) for gaseous emissions from large gas-fired internal combustion engines, has been developed by ANR Pipeline Company (ANR) of Detroit, Michigan. The patented (US Patent #5,703,777) PEMS approach provides an alternative to instrumental continuous emissions monitoring systems (CEMS), and is potentially more cost effective. In addition to monitoring emissions of carbon dioxide (CO_2), carbon monoxide (CO), total hydrocarbons (THC), oxygen (O_2), and nitrogen oxides (NO_x), the ANR PEMS provides feedback on engine operating conditions which influence continuous emissions. The parametric approach to determining air emissions is provided for in 40 CFR Part 64. With over 13,000 natural gas compressors operating in the United States alone, the potential applicability of this system is significant.

The remainder of this section describes the specific verification goals for this project. Section 2 presents a description of the ANR PEMS tested, a description of the test site, documentation of the PEMS installation and set-up, and procedures used for evaluating each of the verification parameters. Section 3 presents the results of the tests conducted. An assessment of data quality is presented in Section 4. Section 5 contains ANR comments on the test results and additional vendor supplied performance data on the PEMS.

1.2 VERIFICATION GOALS

The PEMS approach to monitoring exhaust emissions is based on establishing relationships between engine operating parameters, as determined by commonly used sensors, and exhaust emissions. As such, PEMS are fundamentally computerized algorithms that describe the relationships between operating parameters and emission rates, and which estimate emissions without the use of continuous emission monitoring systems. With this in mind, verification goals and parameters were developed to facilitate an evaluation of this system over a full range of normal and off-normal engine operating conditions. The verification parameters included the following:

- PEMS relative accuracy: This parameter represents the accuracy of PEMS emissions output compared to EPA reference methods for $NO_{X,}$, CO, CO_2, and THC.

- PEMS prediction capabilities during off-normal engine operation: This parameter represents the PEMS prediction accuracy while physically perturbing combustion air manifold temperature and pressure, engine efficiency, and ignition timing.

- PEMS ability to respond to sensor failure: This assessment examines the PEMS ability to predict emissions when one or more of the engine sensors used to predict emissions has failed or is responding incorrectly.

- PEMS diagnostic capabilities: Using data collected in support of the three verification parameters listed above and observations made during testing, this parameter assesses the value of the PEMS in alerting engine operators to operating conditions which could produce excess emissions or other engine problems.

These parameters were assessed through observation, collection and analysis of emissions data generated by the PEMS at an industrial site, comparative EPA reference method gas measurements, engine data logs, and evaluation of ANR-supplied data used to characterize test engine operations.

2.0 TECHNICAL BACKGROUND AND VERIFICATION APPROACH

2.1 ANR PEMS DESCRIPTION

The PEMS approach to monitoring exhaust emissions is based on relationships established between engine operating parameters, as reported by existing engine sensors, and exhaust emissions. The ANR PEMS is applicable to large gas-fired IC engines. Different engines have unique operating characteristics and there are unique relationships between emissions and operating parameters for each engine. Therefore, the PEMS must be specifically calibrated for the engine type on which it will be used. This calibration must be based on comparisons with instrumental measurements representing a range of normal and off-normal operating conditions. This process is referred to as "mapping" the PEMS, and was completed by ANR prior to the start of the test. Thus, the PEMS used in this verification contains relationships unique to the host site engine.

For reciprocating engine applications, the PEMS is typically developed to predict CO_2, NO_x, CO, and THC (as methane) emissions in engine permitting units of grams per Brake Horsepower-hour (g/BHp-hr). The PEMS can also be designed to predict pollutant concentrations in units such as parts per million by volume dry (ppmvd) or percent.

The primary PEMS relationships are a function of engine speed and engine load (as torque). Additional operational parameters used by the PEMS to determine emissions include engine efficiency, ignition timing, combustion air manifold temperature, and combustion air manifold pressure. On this engine, efficiency is defined as the ratio between calculated fuel consumption (based on measured engine speed and torque data) and actual fuel consumption measured with a flow meter.

Figure 2-1 illustrates general PEMS functionalities. Engine speed and torque are the primary determinants of emissions and define the "baseline" emissions profile for the engine. This baseline is representative of a normally functioning and well-tuned engine. As engine operation changes, indicators of engine efficiency, ignition timing, air manifold temperature, and air manifold pressure are used to adjust the emission values. Within the ANR PEMS, monitored and estimated values for these four key parameters are used to increase or decrease predicted emission from the baseline level.

Figure 2-2 illustrates PEMS operational steps and outputs. The ANR PEMS provides several different functions including the prediction of continuous emissions, the reporting of total emissions and high emission alarms/alerts, the monitoring of engine sensor performance, and the reporting of potential sensor malfunctions. ANR has found that combustion air temperature and combustion air pressure are the two engine operating parameters with the greatest effect on emissions. Therefore, the ANR PEMS uses redundant engine monitoring sensors for these parameters. This redundancy provides for assessment of sensor drift and identification of failed or malfunctioning sensors. Seasonal or climate variations are not expected to affect PEMS performance because the parameters having the greatest effect on emissions (such as air and fuel pressure and temperature) are controlled.

Table 2-1 provides specifications for the engine sensors used by the ANR PEMS in this test. Sensor calibration data are presented in Appendix D.

Figure 2-1. ANR PEMS Operational Features

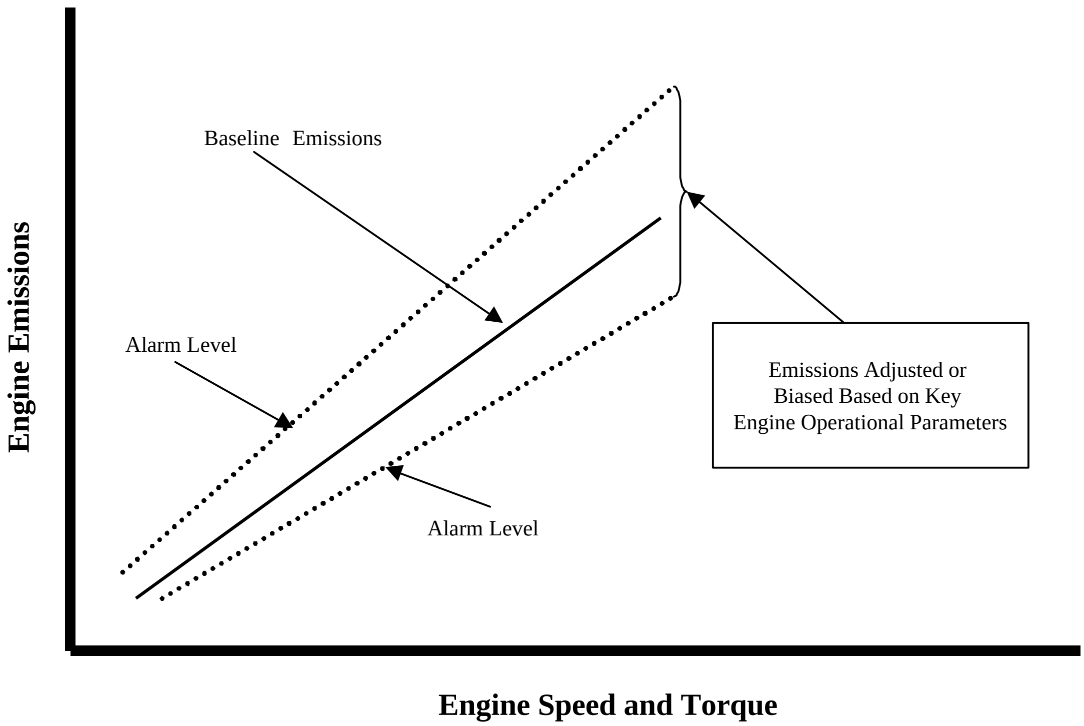


Figure 2-2. Simplified PEMS Diagram

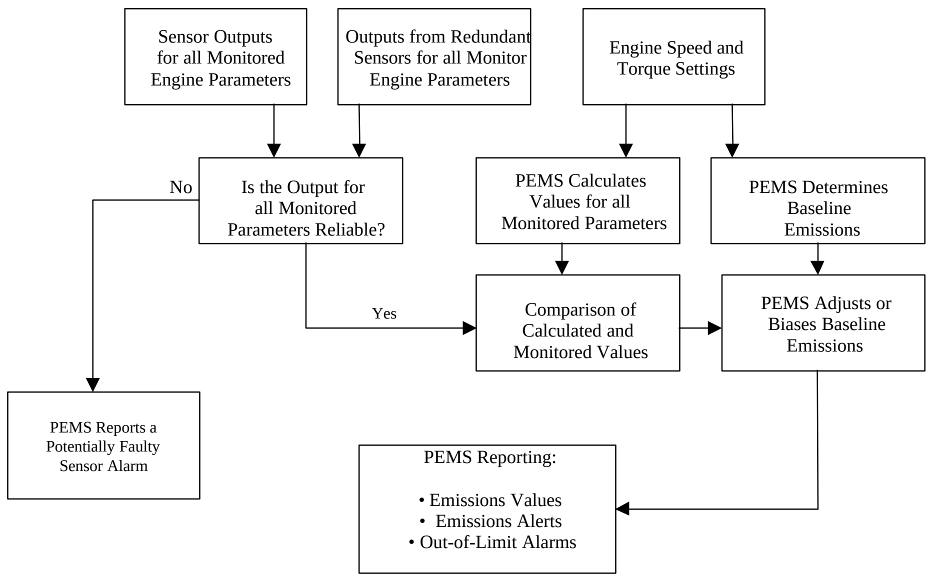


Table 2-1. Engine Parameters/Sensors Used by PEMS

Parameter	Sensor	Specified Accuracy (% FS)	Calibration Check	Operating Range
Ignition timing	Altronic #DI-1401P	$\pm$ 1.00	Annual	45^{o} BTDC to 45^{o} ATDC
Fuel DP (flow)	Rosemount #1151DP-4-S-12-MI-B1 transducer	$\pm$ 0.25	Annual	0-100 in. water
Fuel temperature	Rosemount #444RL1U11A2NA RTD	$\pm$ 0.25	Annual	0-125 ^{o}F
Air manifold pressure	Electronic Creations #EB-010-50-1-0-40/N transducer	$\pm$ 0.25	Annual	0-25 psig
Air manifold temperature	Rosemount 0068-F-11-C-30-A-025-T34 RTD	$\pm$ 1.00	Annual	0-150 ^{o}F

Alarms and alerts are set within the PEMS to alert the engine operator when one or more key operating parameters is out of specified limits. These alarms/alerts are set by ANR specifically for the desired operating rates. Key parameters that have alarm/alert functions include: efficiency (high and low), ignition timing deviation from set point, air-to-fuel ratio deviation from set point, and exhaust gas temperature absolute value (high and low). Table 2-2 lists the actual alert and alarm set points for the test engine.

Table 2-2. Engine Sensor Alarm and Alert Levels

		Alert	Alarm
Efficiency	High	104%	106%
	Low	96%	94%
Ignition Deviation from Set Point		+/- 0.3^{o}	+/- 0.4^{o}
Air Manifold Temperature Redundant Transmitter Deviation		+/- 2 ^{o}F	+/- 4 ^{o}F
Air Manifold Pressure Redundant Transmitter Deviation		+/- 0.15 psi	+/- 0.20 psi

Typically, ANR uses a Bristol-Babcock Series 33 industrial computer running Accol™ software for process control and PEMS functions. The Accol software package serves as an automated data acquisition system for the PEMS, with the predictive calculations implemented within the software.

PEMS alarm/alert functions are also implemented with Accol. Accol can monitor and store all types of engine data in addition to those required by the PEMS. These additional data can be used for engine performance monitoring and diagnostics. For this verification, the system was enhanced by use of the Monitrend Software™ package (by Monico, Incorporated) which provides additional display, data logging, and data reduction capabilities. The Monitrend package is not required for PEMS operation and does not affect PEMS capabilities.

For the test engine, the parameters monitored and stored by Monitrend include:

- Speed - RPM
- Torque - (calculated from gas pipeline compression work) - Ft-lbs
- Torque - (calculated from fuel consumption) - Ft-lbs
- Combustion Air Manifold Pressure - psig
- Ignition Timing - (measured value of #1 cylinder ignition) - ^{o}BTDC
- Efficiency - (calculated fuel divided by actual fuel) - %
- Combustion Air Manifold Temperature - ^{o}F
- Exhaust gas temperature, standard deviation (EGT Std. dev. usually taken at each cylinder port.) - ^{o}F
- Fuel Flow - SCFH
- Turbocharger Speed - RPM
- Turbocharger Outlet Air Temperatures - (both pre and post intercooler) - ^{o}F
- Turbocharger Inlet and Outlet Exhaust gas temperatures - ^{o}F
- Turbocharger "bypass" - (controls Air to Fuel ratio of the engine) - % Open
- Hickok Ignition Monitor - (measures breakdown voltage and glow duration of each spark plug) - kV & msec.
- Vibration - (Multi-points)
- Fuel Manifold Pressure - psig
- Oil & Coolant Temperatures - ^{o}F
- Gas Transmission Pipeline Suction and Discharge, Pressure and Temperatures - psig and ^{o}F

The system samples each variable at 1-second intervals, and can report and record one-minute, one-hour, or daily average values. Digital files containing 30-second average values for each monitored parameter can be archived for specified time periods.

2.2 SITE DESCRIPTION AND SITE SPECIFIC PEMS INSTALLATION

The PEMS approach to exhaust emission determinations requires development of engine-specific parameters to account for the design and operating characteristics of each engine type upon which it is installed. ANR claims that the PEMS is appropriate to most types and sizes of internal combustion engines and has successfully installed the system on several engine types within the ANR transmission system. Algorithms can be derived empirically that can predict emission rates for each engine type, fuel type, and engine location. Thus, engine characteristics were not a significant restriction or limiting factor for the PEMS verification test. This allowed flexibility in site selection.

The engine/compressor selected for this evaluation is a reciprocating, 4-cycle internal combustion (IC) engine, using natural gas as fuel (Figure 2-3). This Ingersoll-Rand engine (model KVR-616: 16 cylinder, 6000 Hp) is equipped with six reciprocating compressors. As with the engine selection, site location was somewhat flexible. The primary concern was any limitation on engine operation due to extremes of weather. Accordingly, extremes of environment, very hot or very cold, were avoided. The site selected for this test was a mid-western U.S. gas transmission station operated by ANR Pipeline Company.

Figure 2-3. Photograph of Test Engine

The PEMS software was installed and emissions data were mapped during the period of July 12 through 30, 1999. This amount of time is typically needed to thoroughly map engine emissions. Engine operating parameters and emission rates were monitored simultaneously during this period to complete the matrix of previously developed prediction equations. Data were collected by ANR personnel and an emissions testing contractor to support the development of emission relationships. PEMS set-up was conducted by operating under a variety of normal engine speed and torque conditions while simultaneously measuring the emissions of NO_x, CO, O_2, THC, and CO_2 by instrumental methods. The Center did not participate in PEMS development and cannot comment on the integrity of the measurements made throughout this period. However, emission measurements were made with calibrated continuous emission monitors, and these data were used to determine baseline, or normal, emission relationships for various speed and torque conditions.

To develop relationships that predict emissions at other than normal conditions, engine operation was forced to change by overriding automated engine control systems. This allowed the impact of abnormal engine operation on emissions to be characterized. Engine operating parameters varied in this step included combustion air temperature, combustion air pressure, engine operating efficiency (calculated fuel consumption/actual fuel consumption), and ignition timing.

The PEMS was developed to predict emission rates of NO_x, CO, and THC in units of g/BHp-hr, and concentrations of CO_2 as percent. For this verification test program, ANR modified the PEMS output to calculate pollutant concentrations in units of parts per million by volume dry (ppmvd) and CO_2 emissions as g/BHp-hr. The concentration values reported by the PEMS (ppmvd for NO_x, CO, and THC) and CO_2 as mass emissions are calculated by the PEMS based on predicted values for g/BHp-hr, CO_2 concentrations, and unit conversions.

The unit conversions needed to complete these calculations include the fuel f-factor and molar volume conversions as published in EPA Reference Method 19 (40 CFR 60, Appendix A) and a fuel heating value. The fuel heating value of 1,012 Btu per standard cubic foot is the average value measured by ANR for this pipeline during the test period. ANR determines fuel heating value on a daily basis using their own gas chromatograph situated along the pipeline near this station. Exhaust gas O_2 concentrations are also needed to complete this calculation and this particular engine does not have an O_2 monitor. Therefore, the O_2 values used in the above equation were imported to the PEMS from the on-site test contractor used by ANR to assist with the PEMS setup parameterization.

The ppmvd values derived by the PEMS may differ slightly from the comparable reference method values due to the assumptions involved in the conversions. The reference method raw instrumental outputs are in terms of ppmvd, which were converted to g/BHp-hr for comparability with the PEMS predicted emission rates. This conversion was performed in conformance with EPA Reference Method 19 (40CFR60, Appendix A) and used O_2 values obtained by the Center's test contractor and fuel f-factor values derived from daily analysis of fuel gas composition. The mass units are compatible with emissions units normally used at the site. For the relative accuracy tests, comparisons are presented in terms of both units (as specified in the test plan). For the remaining tests, comparisons are given only in mass units. To be consistent with the concentrations measured by the CEMS, 30-second average PEMS predicted values were calculated and stored.

2.3 CONTRACTOR COMPARISON TESTING

To facilitate evaluation of the PEMS capabilities, the Center conducted a contractor comparison test prior to beginning the verification testing. During this test, emission rates were measured simultaneously by the contractor used to set up the PEMS, and the Center's contractor used to conduct the verification testing, Kilkelly Environmental Associates (KEA). The tests were conducted to verify comparability of the data generated by the two contractors. During the comparisons, the two sampling systems were entirely independent of each other, including all sampling system components and both contractors calibrated their instruments with their own calibration gas standards. The two sampling probes were approximately 1-foot apart in the exhaust gas duct.

A total of four comparison test runs were conducted on July 20 to simultaneously determine concentrations of NO_x, CO, THC, and CO_2 in the engine exhaust. The actual and percentage differences were calculated [(KEA reference method - ANR contractor)/KEA reference method] * 100, and are summarized in Table 2-3 with the absolute differences.

Table 2-3. Test Contractor Comparison Results										
	Run 1		Run 2		Run 3		Run 4		Average	
Parameter	**Abs. Diff.**	**% Error**	**Abs. Diff.**	**% Error**	**Abs. Diff.**	**% Error**	**Abs. Diff.**	**% Error**	**Abs. Diff.**	**% Error**
NO_x	60 ppm	8.7	109 ppm	10.7	51 ppm	11.6	54 ppm	12.1	69 ppm	10.8
CO_2	-0.37 %	-7.6	-0.50 %	-10.3	-0.51 %	-10.7	-0.63 %	-13.1	-0.50 %	-10.4
CO	-30 ppm	-8.8	-28 ppm	-10.3	-44 ppm	-11.1	-39 ppm	-10.2	-35 ppm	-10.1
THC	-411 ppm	-73	-373 ppm	-85.9	-545 ppm	-74.1	-582 ppm	-81.4	-478 ppm	-78.6

The differences for NO_x, CO, and CO_2 were slightly higher than the goal of 10 percent specified in the Test Plan. However, Center staff considered the differences reasonable for the purpose of this verification after confirming that they were repeatable and that no significant sample gas collection, transport, conditioning, or analysis errors occurred. The large discrepancy in the THC results, however, was a cause for concern. A substantial effort was expended over several days to determine the cause of the THC discrepancy. KEA results were consistently much lower than results obtained by ANR's test contractor. Exhaustive tests and checks were conducted on KEA's sampling system including the use of spare analyzers, trading of calibration gases, and verification of calibration gas values using an independent portable analyzer. The main goal of the checks was to confirm that the data from the verification test team were valid with respect to EPA Reference Method 25A and all of the quality control and quality assurance specifications therein. Instrument calibration data are summarized in Appendix C and more detail regarding QA/QC procedures are presented in Section 4.0.

Center personnel verified that KEA's THC data were generated in strict accordance with EPA Reference Method 25A (40 CFR 60, Appendix A) and were repeatable using several different analyzers. Because all Method 25A specifications and QA/QC procedures were not followed by the ANR contractor, the Center concluded that the source of the discrepancy was likely in the ANR contractor's data and that the verification team data were reliable. The Center was not provided with copies of the site test contractor's QA/QC data, but the following deviations from the reference method specifications were observed during testing.

- The sample gas stream directed to the THC analyzer was cooled to remove engine exhaust gas moisture. The reference method calls for a heated sample delivery system to prevent condensation and removal of gas moisture.

- Calibrations were conducted only by introducing gas standards directly to the analyzer. System bias was not determined by routing the gas standards through the entire sampling system.

- The analyzer operating range was 0 to 10,000 ppm with measured concentrations ranging from approximately 800 to 1,200 ppm. A range of 1.5 to 2.5 times the expected concentrations is specified in Method 25A.

- Failure to properly optimize the flame of the FID analyzer used as is recommended by most instrument manufacturers.

The exact cause(s) of the discrepancy between the two test teams was never identified, but is presumed to be attributable to one or more of the method deviations listed above. Because the PEMS was developed and mapped using the ANR contractor data, a decision had to be made on how best to proceed in light of the THC discrepancy. It was decided that the schedule did not allow re-mapping the entire THC prediction array previously developed and incorporated into the PEMS. Therefore, ANR personnel and the Center agreed to proceed with the verification testing using existing THC arrays. The revised goal for this pollutant was to evaluate if trends in the PEMS THC predictions correlate with actual THC emissions after changes in engine operation or sensor signals.

2.4 VERIFICATION APPROACH

2.4.1 Relative Accuracy Test

As the PEMS approach to air emissions monitoring is a relatively new technology, it is in limited use. As such, formalized performance demonstration procedures specific to PEMS have not been established to date by U.S. EPA.

Instrumental monitoring systems have been developed to the level that they are a primary means for monitoring gaseous emissions from industrial processes for regulatory compliance purposes. This has led to EPA's development of Performance Specification Test procedures to confirm the precision and accuracy of instrumental monitoring systems. With some augmentations, these EPA Performance Specification Tests can also be used to determine PEMS performance. EPA's Performance Specification Tests were the primary bases used to assess the ANR PEMS monitoring performance. EPA has prepared example specifications and evaluation procedures for assessing PEMS performance (Emission Measurement Center, U.S. EPA), and these guidelines have also been followed here. The Performance Specifications generally require a relative accuracy of 20 percent of the mean reference method value or 10 percent of the applicable emissions standard for a CEMS to be considered functional and able to report accurate emissions. This same standard for relative accuracy of 20 percent of the mean reference method value was used to evaluate the PEMS (there are no applicable emissions standards for the test engine).

EPA Performance Specification Test procedures (40 CFR Part 60, Appendix B) were used to determine the relative accuracy of the PEMS with respect to emission prediction capabilities for NO_x, CO, THC, and CO_2. As required by the Performance Specifications, EPA Reference Methods were used to determine actual pollutant concentrations and emission rates for comparison with the PEMS predictions. The following Performance Specifications and Reference Methods were followed during the testing.

- Performance Specification Test 2 for NO_x: Reference Method 7E
- Performance Specification Test 3 for CO_2: Reference Method 3A
- Performance Specification Test 4 for CO: Reference Method 10
- Performance Specification Test 8 for THC: Reference Method 25A

A continuous extractive system was used to continuously sample engine exhaust gas throughout each designated test period. Two gas streams were directed to the mobile laboratory, with one stream directed through a filter and moisture removal system to condition the gas to a cool and dry state, and another delivered to the laboratory via a heated sample line to provide a hot, moist sample for THC analysis.

In the mobile laboratory, a manifold was used to regulate and direct the desired flow of sample gas to the analyzers. The following table summarizes the analyzers and operating ranges used for this test.

Table 2-4. Reference Method Analyzers

Target Compound(s)	Analyzer Make and Model	Principle of Operation	Operating Range
NO_x	TEI Model 10S	Chemiluminescense	0 - 2,500 ppm
CO	TEI Model 48	Gas Filter Correlation NDIR	0- 500 ppm
THC	JUM Model VE-7	Flame Ionization Detector	0 - 1,000 ppm (as CH_4)
CO_2	Milton Roy 3300	NDIR	0 – 20 %
O_2	Teledyne 320A	Electrochemical Cell	0 – 25%

All of the quality assurance and quality control requirements specified in the reference methods were followed during the testing. Daily calibration error checks were conducted by directing a suite of certified calibration gases directly to the appropriate analyzers prior to starting any tests. The system bias and drift checks conducted before and after each test run were executed by directing the zero and mid-level gases to the sampling probe and routing the gases through the entire sampling system. Measured pollutant concentrations were related to mass emissions in units of g/BHp-hr using EPA Method 19 calculations, fuel f-factors calculated from daily fuel gas composition analyses (conducted by ANR), fuel heat content values reported to the Center on a daily basis (also measured by ANR), and engine control center horsepower and fuel flow signals averaged for each test period.

Prior to conducting the relative accuracy testing, the reference method and PEMS clocks were synchronized and the sampling system response time was determined to ensure representative comparisons. Because the response times for all reference method test parameters were less than one minute, no adjustments were made to test start times. Additionally, an oxygen stratification test was conducted in the engine exhaust duct to confirm the absence of gas stratification. Because stratification was not detected (testing was conducted downstream of the turbocharger), the reference method testing was conducted at a single point within the duct.

Prior to conducting the relative accuracy (RA) tests, ANR personnel confirmed that the engine was operating normally and in a well-tuned state. A total of 12 test runs, each 21 minutes in duration, were conducted in order to determine RA for each gas. Because engine speed and torque are primary determinants of engine emissions, the test plan specified that tests be conducted while operating this engine at four different operating conditions within its normal operating range. The target RA test matrix is given in Table 2-5.

Table 2-5. Planned Relative Accuracy Test Matrix

Number of Tests	Engine Speed (rpm)	Engine Torque (%)
3	263 – 315	75 – 90
3	263 – 315	90 – 100
3	315 – 350	75 – 90
3	315 – 350	90 – 100

2.4.2 PEMS Prediction Capabilities During Off-normal Engine Operations

Tests conducted during the relative accuracy testing were used to verify PEMS performance during normal engine operating conditions. However, mechanical failures or changes, changes in fuel properties, and changes in ambient conditions can change engine performance and emissions relative to normal operations. In order to evaluate the PEMS ability to respond to off-normal engine operations, a series of tests were conducted while physically perturbing several key engine sensors. These perturbations in turn affected the control system, which acted in a complex way to change the operating characteristics of the engine.

The parameters of engine operation having the most significant effect on emissions include air manifold pressure and temperature, exhaust manifold pressure and temperature, ignition timing, engine efficiency, and relative humidity. Exhaust manifold temperature and pressure cannot be controlled in a predictable manner, and relative humidity cannot be controlled or easily simulated. Therefore, the off-normal testing only included physical perturbations to air manifold temperature and pressure, ignition timing, and engine efficiency. Engine perturbations were performed using the following procedures:

- Combustion air manifold temperature and pressure - Air manifold temperatures were varied by manually changing the temperature setting, causing the engine to increase or decrease air flow through the heat exchanger (turbocharger jacket). Both high and low temperatures that are close to the upper and lower air temperature alarm levels were easily established. Air manifold pressure was changed by increasing or decreasing combustion air flow to the engine.

- Engine efficiency - Assessment of engine efficiency is used to determine if the engine is performing properly. The most effective way for an efficiency perturbation to be introduced to the PEMS is for the engine to do more or less work than the computer senses. Computer-based engine efficiency is an engine operating indicator defined as the calculated fuel consumption (based on measured engine work and RPM, which yields horsepower) divided by the measured fuel consumption. To demonstrate efficiency perturbations, the horsepower (i.e., the work accomplished by the engine) was changed. This in turn caused a change in actual fuel flow while the computer was still sensing the original unchanged horsepower. The actual engine thermodynamic efficiency hadn't changed, thus the efficiency value the computer calculated changed. By blinding the computer to the actual engine horsepower in this way, the efficiency was altered above or below the nominal value of 100 percent. The benefit of the efficiency function is to enable the PEMS to react to degradations of the compressors, which in turn determine engine load.

- Ignition timing - Ignition timing was manually adjusted to vary this operating parameter. As above, values just short of upper and lower alarm values were established.

Emission changes occurring as a result of changes in the operating parameters listed above may vary in significance depending on engine torque and speed settings. Recognizing this, these engine parameters were perturbed at three different torque and speed operating regimes. This resulted in a total of 24 individual test runs during off-normal engine (i.e., conditions outside of normal controller response) operations. The design test matrix is summarized in Table 2-6.

Table 2-6. Off-Normal Engine Operating Test Matrix

Operational Parameter/Alarm Condition		Approximate Engine Speed/Torque Settings		
		350 rpm / 100%	280 rpm / 100%	350 rpm / 75%
Efficiency (%)	High	x	x	x
	Low	x	x	x
Ignition Timing (degrees)	High	x	x	x
	Low	x	x	x
Air Manifold Temperature (^oF)	High	x	x	x
	Low	x	x	x
Air Manifold Pressure (psig)	High	x	x	x
	Low	x	x	x

X – denotes individual test runs

The same reference methods and QA/QC procedures used for the relative accuracy testing described in Section 2.4.1 were followed for these tests. Each run was at least 21 minutes in duration after stable operating conditions were attained at the desired torque and speed setting. During each test run, the engine was allowed to stabilize with respect to parameters and emissions. The engine was then perturbed by ANR personnel either above or below the normal set points using the methods described above. The engine components were perturbed so that either an alarm or alert was reported by the PEMS for that parameter. This test scenario was then repeated by perturbing the particular engine parameter in the opposite direction. Reference Method and PEMS emissions data were collected throughout each test period for comparison.

2.4.3 PEMS Response to Sensor Failure

In order to evaluate the PEMS ability to respond to sensor failure or drift, another series of tests was conducted which included perturbations to key engine sensors important to PEMS functions. By changing the electronic signal received by the PEMS from the sensors, failure and/or drift of the sensors was simulated. The sensors perturbed during this series of tests included ignition timing, engine efficiency (fuel flow sensor), air manifold temperature, and air manifold pressure. Engine efficiency is a calculated value based on the fuel flow sensor value.

The sensor signals are directed from the engine to the engine operating software (Bristol Babcock's Accol software) prior to being routed to the PEMS. The sensors were perturbed by intercepting the sensor output signals received by the PEMS , and electronically adjusting the signals using the control inhibit mode of operation built into the Accol software. Sensors were adjusted both above and below the baseline signals received from the engine.

Separate test runs were conducted for each sensor while simulating sensor drift both above and below normal levels. At the beginning of each test, baseline data were collected for a 10-minute period during steady state engine operations. For these tests, steady state operation is defined as normal operation at speeds of around 320 rpm and loads of approximately 85 percent torque. The 10-minute baseline period was followed by a series of stair-step perturbations to levels that reached parameter alert and/or alarm levels. Ten minutes of emissions data were collected during each step perturbation resulting in test durations of up to 40 minutes, depending on the number of step perturbations achieved.

This resulted in a series of eight single-sensor perturbation test runs (four sensors perturbed in two different directions). In order to assess the impact of multiple failed sensors, this entire procedure was then repeated for pairs of simulated sensor failures. The sensors were perturbed for all combinations of pairing of the four sensor types. This resulted in a total of 12 more sensor perturbation tests. During each of these tests the following data were recorded and provided to the Center.

- Default or conservative emission values reported by PEMS,
- Perturbed sensor signal values,
- All other sensor values,
- PEMS concentrations and emission rates for all pollutants,
- Alarm/alert conditions reported by the PEMS, and
- Reference Method concentrations and emission rates for all pollutants.

A tabular summary of the tests conducted is presented in Appendix A. The test plan originally specified that these tests would include evaluation of sensor perturbations to five sensor types. However, because this engine was not equipped with an exhaust manifold pressure sensor, only four sensors were evaluated. Likewise, this reduced the number of double sensor perturbation tests from 20 to 12.

2.4.4 PEMS Diagnostic Capabilities

Data collected as described in Sections 2.4.2 and 2.4.3 were used to assess how well PEMS provides diagnostic information that engine operators can use to identify and rectify engine operating and sensor problems that may negatively impact emissions.

Section 2.4.2 described how data would be collected when actual engine malfunctions were occurring. These data were used to assess PEMS ability to warn of poor engine performance and subsequent emission increases. PEMS alarms and alerts recorded under the sensor failure analyses described in Section 2.4.3 are used to qualify how well PEMS alerts operators to the existence of failed sensors, or to the possibility that a sensor is drifting significantly.

3.0 VERIFICATION RESULTS

3.1 RESULTS SUMMARY

This section provides a brief summary of some of the important conclusions discussed in the following four sections. First, the results of the relative accuracy testing and the graphic representation of the RA test results over time clearly show the PEMS ability to predict NO_x, CO_2, and CO emissions within the accuracy specifications applicable to a continuous emissions monitoring system (CEMS). The calculated relative accuracies for NO_x, CO, and CO_2 were well within the EPA Performance Specifications of 20 percent that would apply to CEMS in this application, indicating that the PEMS has excellent emission prediction capabilities for these parameters.

Although the PEMS NO_x predictions were somewhat erratic while forcing off-normal engine operations, the PEMS NO_x predictions were relatively accurate (within 12 percent) over a wide range of engine operating regimes. Furthermore, the test data support ANR's claim that, when the PEMS does not track actual NO_x emission rates closely, it reports emissions conservatively.

Because of the disparity between the two test contractors (the PEMS development team and the verification team), results of the THC testing are somewhat inconclusive. Although the RA for THC was approximately 34 percent, the PEMS did respond to changes in engine speed and torque settings by predicting higher THC emission rates during the high engine speed operating conditions, which correlates with the reference method measurements.

Very little variability in CO_2 emissions was measured throughout this testing and the PEMS performed very well in predicting CO_2, with differences within 5 percent of the reference method results. The PEMS also tracked measured CO emissions closely following torque and/or speed changes and was consistently within 7 percent of the reference method data.

The single and double sensor perturbation tests had little or no impact on emissions other than NO_x, and PEMS predictions were accurate for CO and CO_2. Where redundant sensors were tested, the PEMS defaulted to the sensor that predicts NO_x emissions conservatively.

The PEMS contains alarm/alert functions that provide diagnostic capability. At the test site, as at many compressor stations, engine sensor alerts and alarms are already implemented in the station control system and, in such cases, the PEMS may not provide additional engine sensor alarm/alert capability. However, the use of redundant sensors by the PEMS does enhance diagnostic capability over what would otherwise be available. In addition, the PEMS provides a capability to readily assess and track changes in engine operations in terms of emissions.

3.2 RELATIVE ACCURACY DETERMINATIONS

A total of 12 test runs, each 21 minutes in duration, were conducted in order to determine the relative accuracy of PEMS predictions for each gas. The four engine speed and torque conditions maintained throughout the RA testing are summarized in Table 3-1.

Table 3-1. Engine Operations During Relative Accuracy Tests		
Run Nos.	**Engine Speed (rpm)**	**Engine Torque (%)**
1-3	280	83.5
4-6	350	82.1
7-9	280	92.7
10-12	343	92.5

Engine operational problems or PEMS alerts or alarms were not encountered during the RA testing. Because no upsets were encountered, all 12 tests are included in the RA calculations for PEMS predictions in units of g/BHp-hr, even though the Performance Specifications contain provisions that allow three runs to be discarded. Run 1 was not included in the RA for ppm-based results due to abnormal O_2 values during the test (the O_2 values are used to calculate ppm from g/BHp-hr). As mentioned earlier, the PEMS was using the engine mapping test contractor's O_2 analyzer for this parameter. It appears that during Run 1 the contractor allowed ambient air to enter the sampling system momentarily. The PEMS RA for each test parameter expressed in units of g/BHp-hr and ppmvd are summarized in Table 3-2. The table also presents the mean absolute differences between the Reference Method data and the PEMS predictions, and the standard deviation of the differences. More details regarding the RA test results are summarized in Appendix B including Reference Method measurements and PEMS predictions of emission rates for each test run.

Table 3-2. Relative Accuracy Test Results						
	g/BHp-hr			**ppmvd/% for CO_2**		
Parameter	**Mean Diff.**	**Std. Dev.**	**RA (%)**	**Mean Diff.**	**Std. Dev.**	**RA (%)**
NO_x	0.60	0.14	11.1	71.4	26.9	11.2
CO_2	10.9	7.41	3.90	-0.36	0.08	8.18
CO	-0.07	0.05	6.78	-12.9	9.61	6.38
THC	-0.63	0.12	34.2	-220	52.0	33.6

The calculated RAs for NO_x, CO, and CO_2 were well within the EPA Performance Specifications of 20 percent that would apply to CEMS in this application, indicating that the PEMS has excellent emission prediction capabilities for these parameters. The calculated RA for THC was well outside of 20 percent, but a difference between PEMS and reference method values was expected due to the off-set between test contractors (see Section 2.3).

The percent differences are defined as the average difference between actual emissions (reference method value) and predicted emissions (PEMS output) divided by the reference method value and multiplied by 100. Test results for each pollutant and each test run during the relative accuracy test audit (Rata) tests are presented graphically in Figures 3-1 through 3-4. Figures 3-1 and 3-2 present g/BHp-hr based results for both absolute values and percent difference. Figures 3-3 and 3-4 include concentration results in units of ppmvd. The figures also display the torque and speed as percent of capacity during each test run (350 rpm is full capacity for engine speed).

Figure 3-1. Rata Results as Percent Difference (g/BHp-hr)

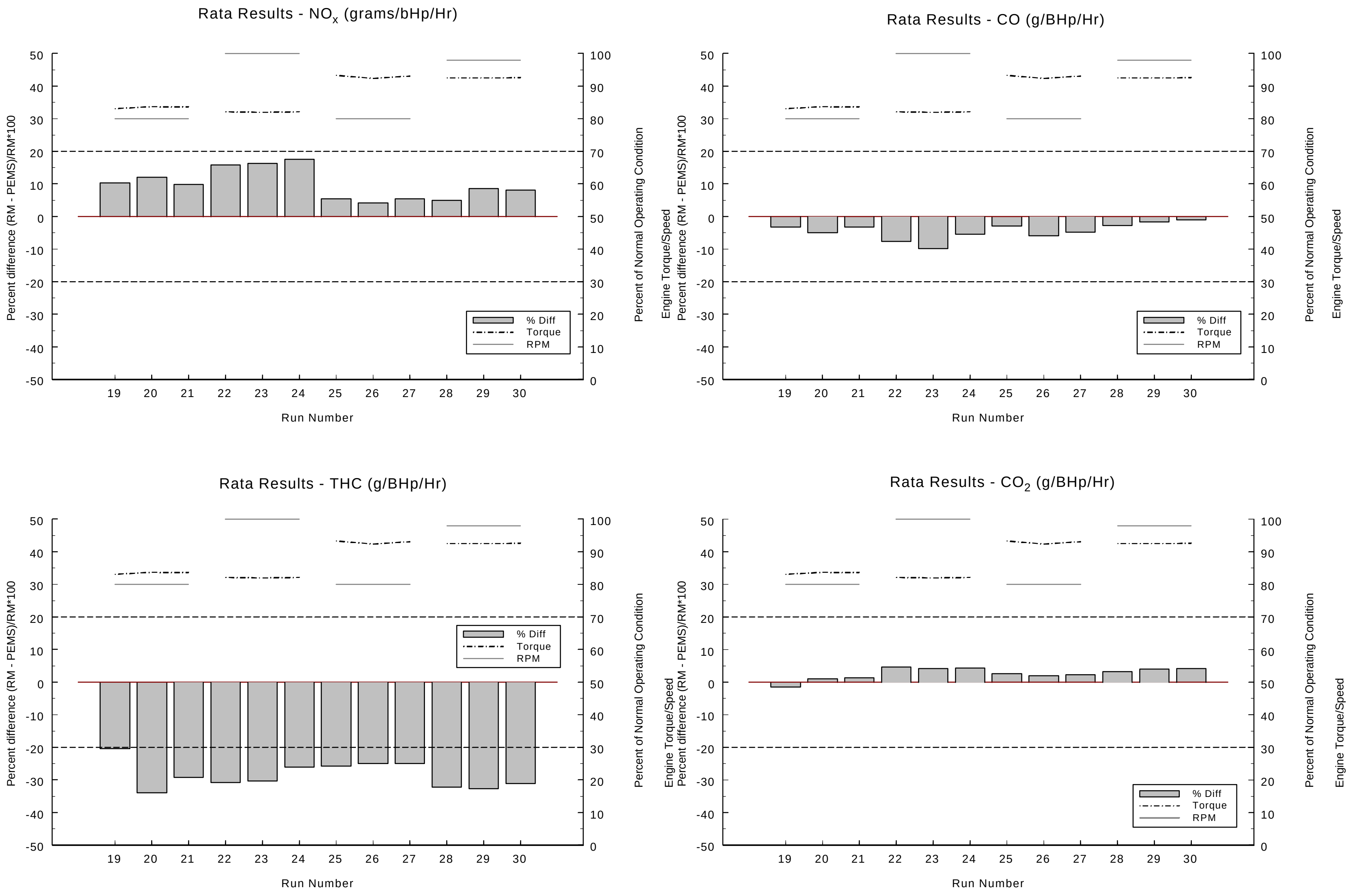


Figure 3-2. Rata Results as Absolute Values (g/BHp-hr)

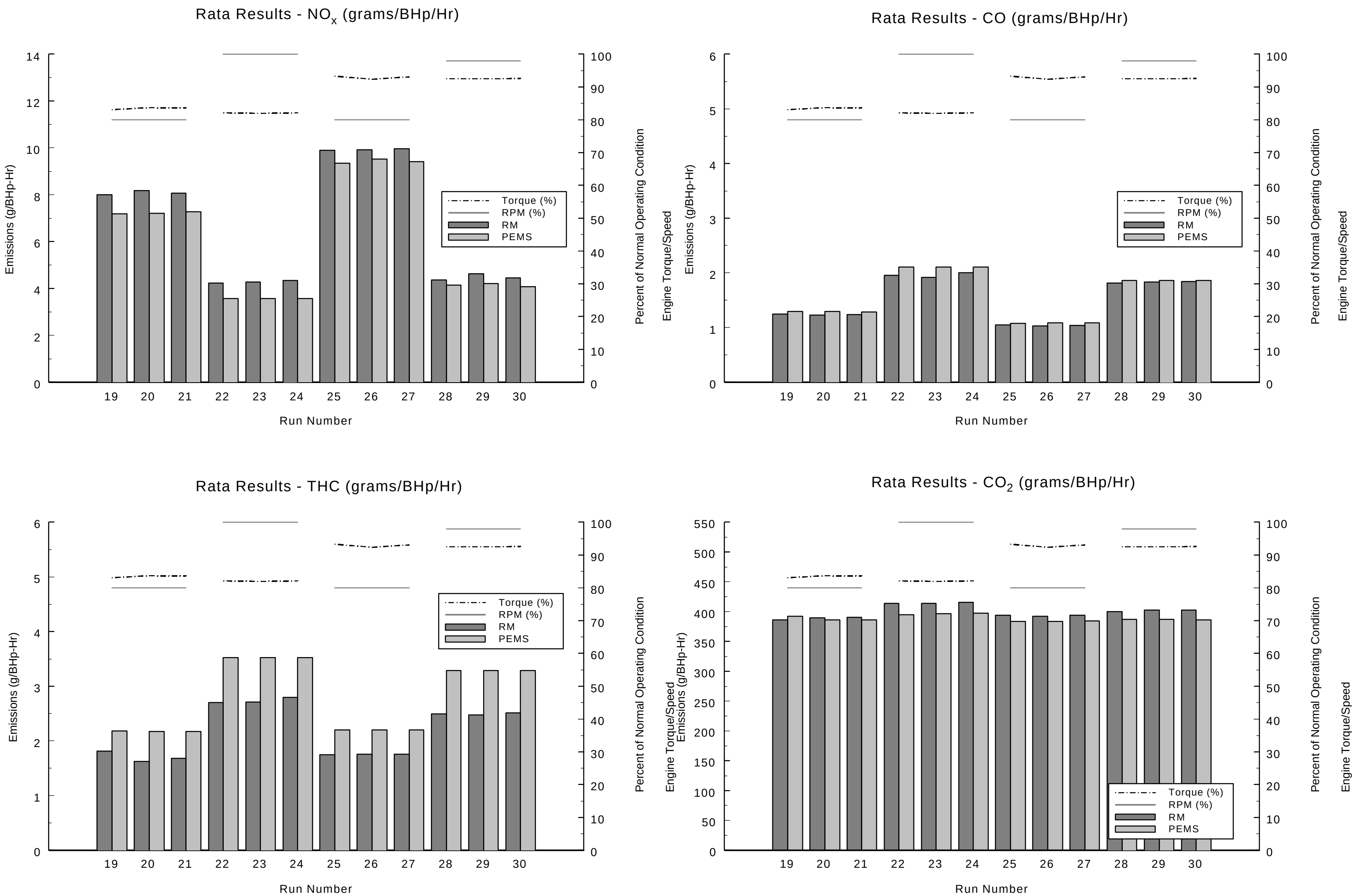
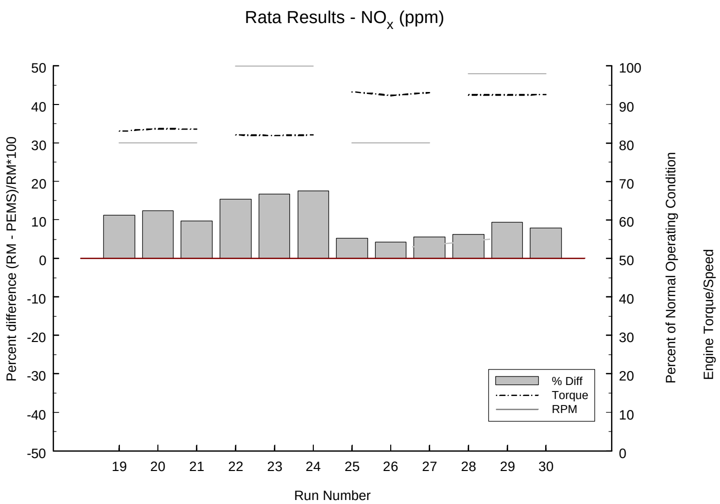
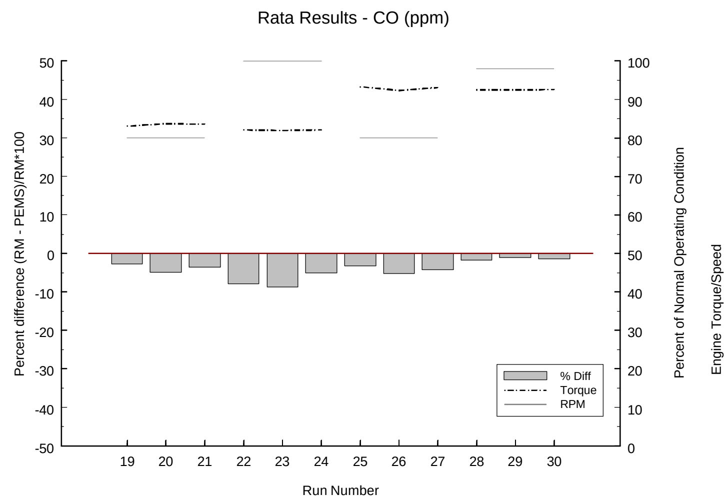
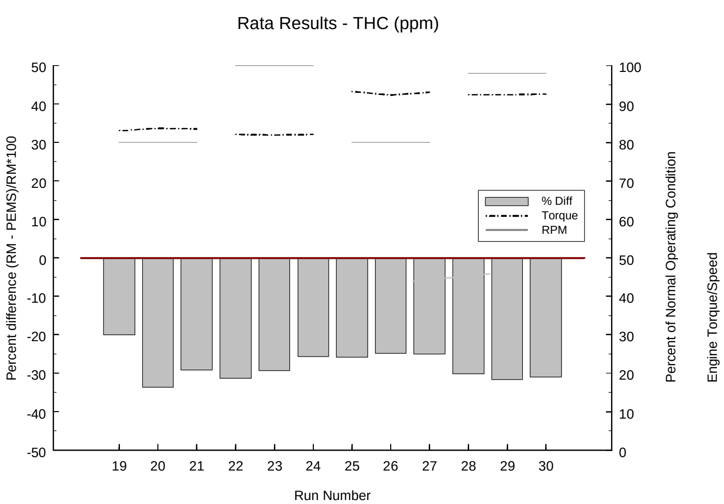


Figure 3-3. Rata Results as Percent Difference (ppmvd)







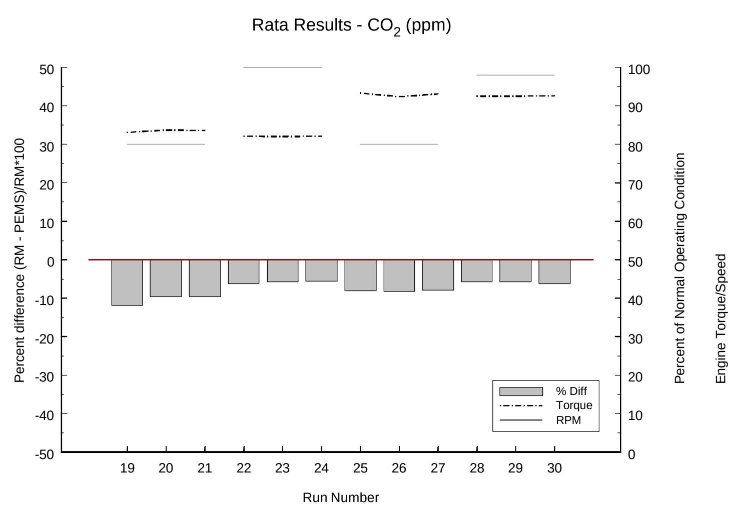
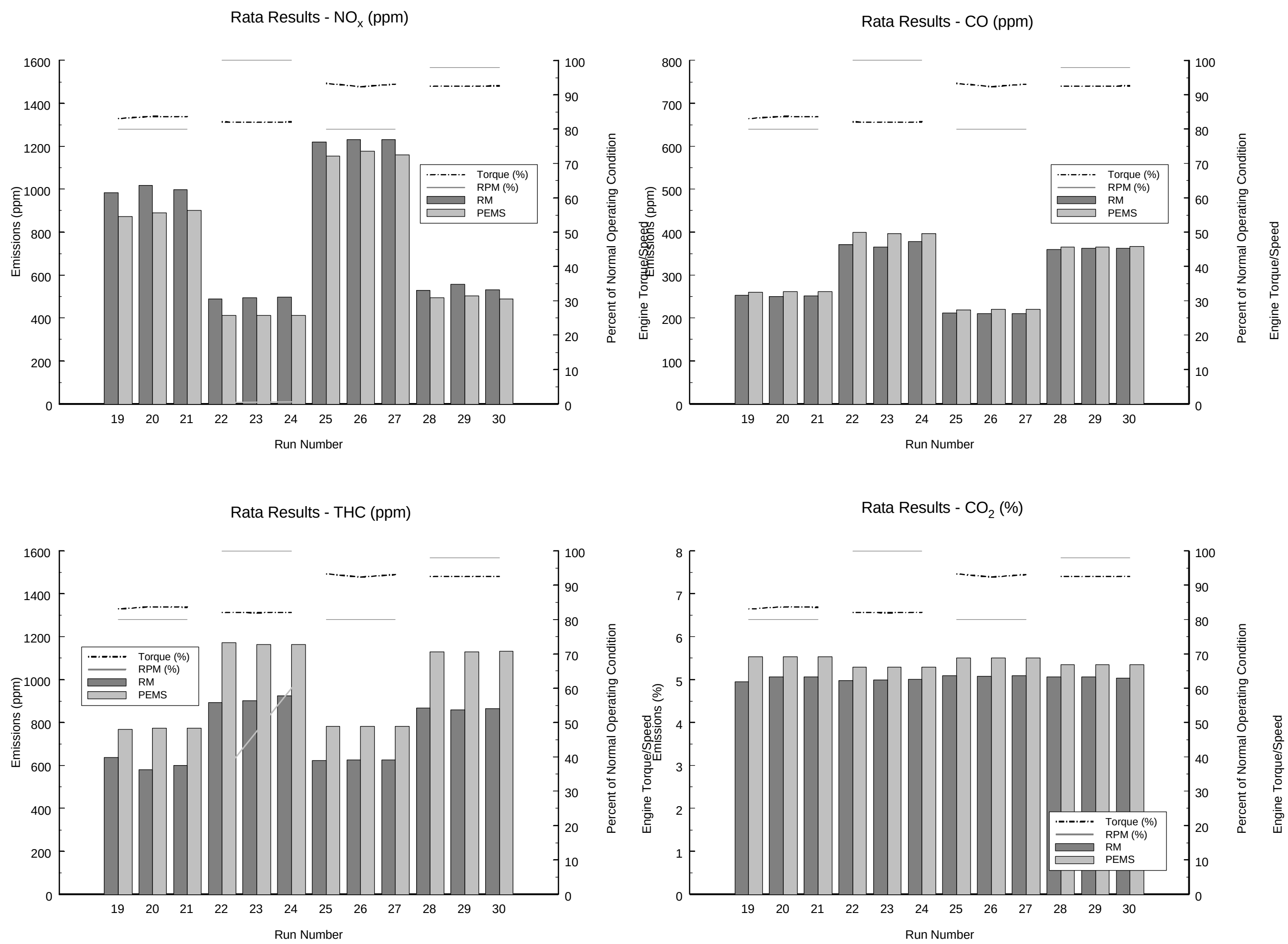


Figure 3-4. Rata Results as Absolute Values (ppmvd)



As illustrated in Figures 3-1 through 3-4, engine operating set points with regards to engine speed and torque had no significant effect on the differences between measured and predicted CO and CO_2 levels, and a minimal effect on NO_x differences. This is significant given the fact that actual NO_x emissions were approximately twice as high during the low speed engine tests as they were during the high speed tests. The percent difference between measured and predicted NO_x was highest (averaging approximately 15 percent) during the low torque/high speed operating point when actual NO_x emissions were lowest (Runs 22 through 24). With regards to NO_x predictions, this particular engine was formerly a 16 g/BHp-hr engine before ANR installed a mixing kit to reduce emissions to current levels. Generally, as engine emissions drop and other sensed variables remain fixed, achieving acceptable RA levels becomes more problematic. Measured CO emissions were approximately 50 to 60 percent higher during the high engine speed test conditions, but PEMS CO predictions were always within 10 percent of the reference method values. The PEMS successfully predicted NO_x and CO emissions over a wide range.

The percent differences between PEMS CO_2 predictions and measured CO_2 were significantly different for the two reporting units. The calculated RA was 8.18 percent for concentration (PEMS predictions were higher than the reference method) and 3.90 percent for mass emissions (PEMS predictions were lower). This was caused by an inconsistency in the PEMS CO_2 calculation. In the PEMS conversion from concentration to emission rate, the lower heating value of the fuel gas (916 Btu/cf) was used instead of the higher heating value of 1,012 Btu/cf that was used for the other pollutants. ANR is now aware of this calculation error and will adjust the equation. Had the HHV been used in the calculation, the RA results for CO_2 mass emissions would be consistent with that for concentration (approximately 8 percent, with PEMS predictions slightly higher than measured).

Figures 3-5 through 3-8 graph the 30-second average pollutant concentrations (ppmvd or percent) generated by the PEMS and the reference method for the entire RA test period (excluding the first test run).

Figure 3-5. Predicted and Measured NO_x Concentrations During Rata Testing

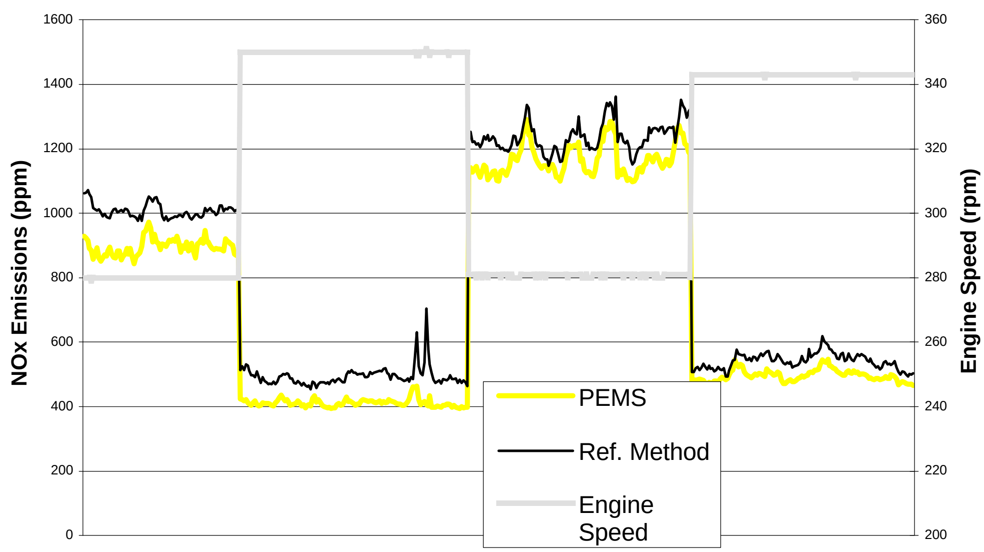


Figure 3-6. Predicted and Measured CO_2 Concentrations During Rata Testing

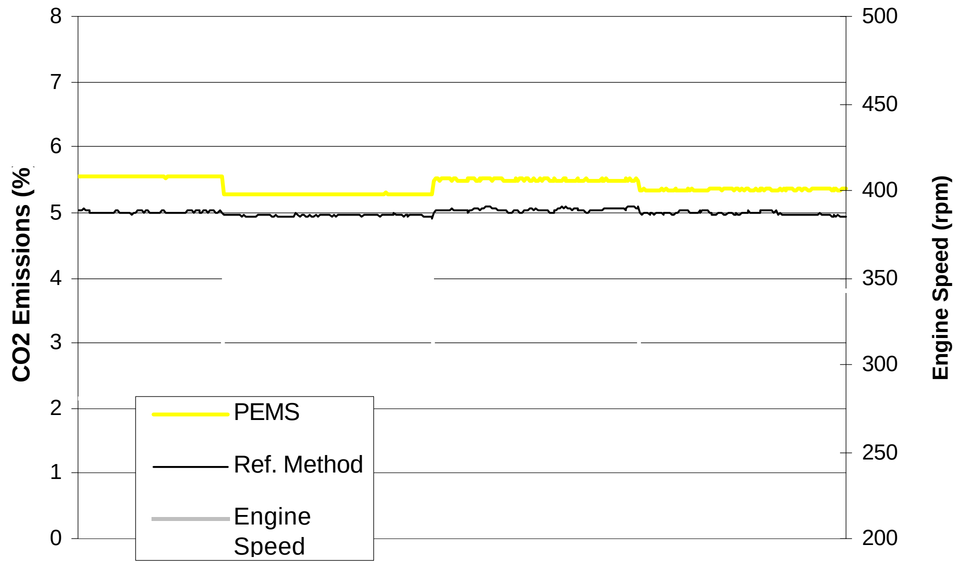


Figure 3-7. Predicted and Measured CO Concentrations During Rata Testing

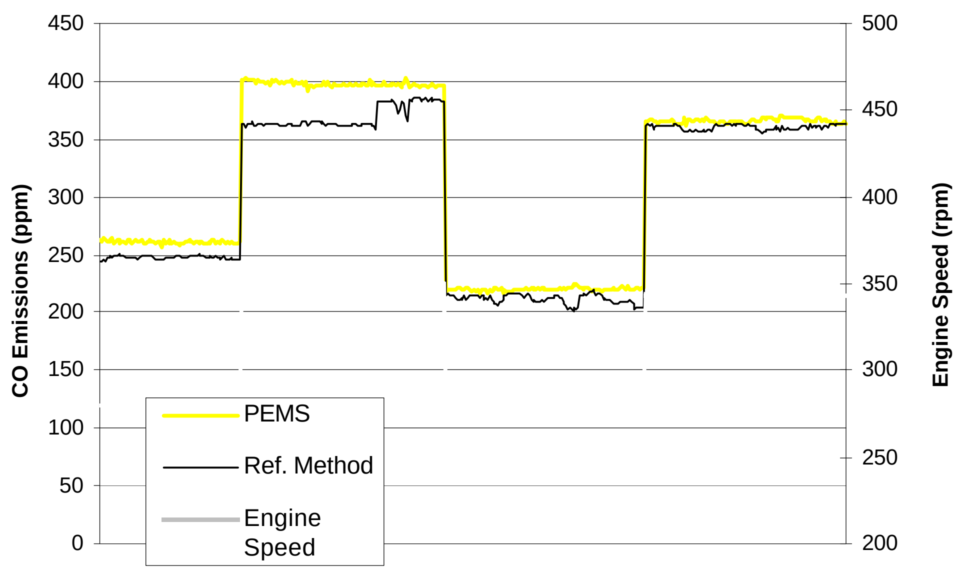
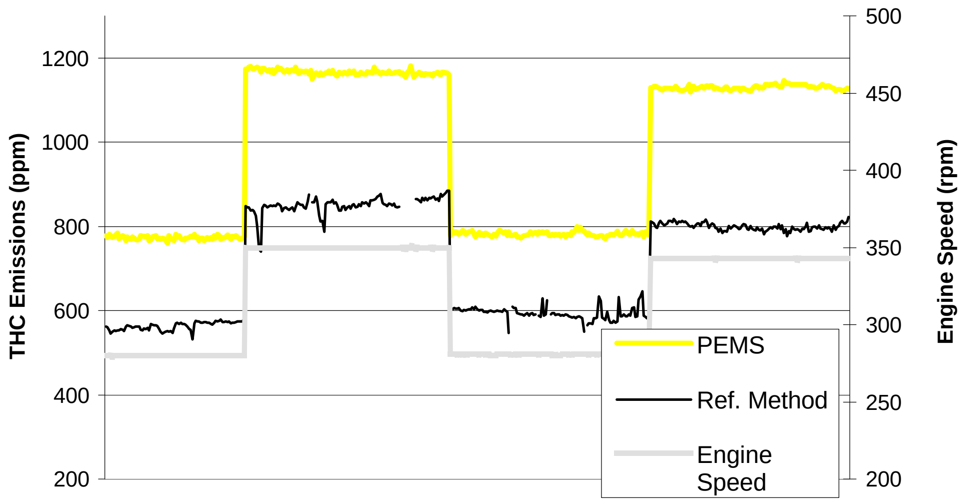


Figure 3-8. Predicted and Measured THC Concentrations During Rata Testing



These graphic representations of the Rata test results over time illustrate the PEMS ability to predict continuous NO_x, CO_2, and CO emissions within the specified accuracy of EPA Performance Specifications for CEMS. Most notable is Figure 3-5 for NO_x emissions because of the variability in NO_x concentrations measured using the Reference Method. Figure 3-5 clearly demonstrates the PEMS ability to accurately track measured NO_x emissions in the presence of small scale, and large scale emission variations.

Very little variability in CO_2 emissions was evident in the Reference Method data, even after engine speed and torque changes. Small scale variations were insignificant and large scale variations were minimal after speed changes. Figure 3-6 shows that the PEMS overcompensated slightly for changes in engine operation. PEMS predictions of CO were very good with regard to the large scale variations that occurred in the Reference Method data after engine speed changes (Figure 3-7). However, there were some smaller scale variations in the measured CO emissions that the PEMS apparently did not respond to.

The differences between the PEMS predictions of NO_x, CO_2, and CO emissions are comparable to the differences observed between the two contractors during the comparison testing as illustrated in Table 3-3.

Table 3-3. Comparison of Percent Differences

Parameter	Contractor Difference (%)	RA Difference (%)
NO_x	10.8	11.2
CO_2	-10.4	-8.18
CO	-10.1	-6.38
THC	-78.6	-33.6

These data further support the PEMS prediction capabilities for NO_x, CO_2, and CO by suggesting that the differences observed during the RA tests are a function of the difference between the two contractors.

Discrepancies in THC emissions measured by the PEMS development test system and the reference method system were addressed in Section 2.3. The THC discrepancy between contractors was approximately 79 percent, as shown in Table 3-3, but during verification testing the difference between contractors was only about 34 percent for THC (the contractor differences for all other pollutants were consistent during the comparison testing and the verification testing). Supporting data comparing measurements obtained by the two contractors are provided in Appendix B. These findings, combined with the fact that the testing was conducted approximately two weeks after the initial comparison, cast additional doubt on the validity of the THC comparison conducted in July. For these reasons the conclusions of this test are based only on the verification tests conducted in August.

During the RA testing, the PEMS predicted THC emissions were approximately 28 percent higher than the reference method values. The THC emission rates predicted by the PEMS did change in response to changes in engine operations as shown in Figures 3-1, 3-2, and 3-8. However, the percent differences during high-speed engine operation were approximately 31 percent and the percent differences during low-speed engine operation averaged 26 percent. These percent errors were consistent from test to test at each of the four operating set points.

The RA testing conducted on the PEMS resulted in the following conclusions:

- The PEMS predicts NO_x, CO, and CO_2 emissions accurately and consistently within the normal speed and torque operating range of this engine.

- The PEMS has the capability to predict small variations in NO_x emissions.

- The accuracy of the PEMS-predicted emissions are relative to the accuracy of the measurements obtained during mapping.

- The mean NO_x, CO, and CO_2 bias between the PEMS and reference method data was in the same direction and relatively same magnitude as the difference between the two contractors.

- Results of the RA testing for THC are well outside of 20 percent. However, the differences reported are consistent with, and likely related to, differences in THC concentrations measured by the two contractors during the testing. The results do show that THC predictions are consistent at a given engine operating regime and the PEMS does respond to changes in engine speed by predicting higher THC emissions during higher engine speed operations.

3.3 PREDICTION CAPABILITIES DURING OFF-NORMAL OPERATION

To evaluate the PEMS ability to respond to off-normal engine operations, a series of tests were conducted while physically perturbing several key engine-operating characteristics. The off-normal testing included physical perturbations to air manifold temperature and pressure, ignition timing, and engine efficiency. These engine parameters were perturbed both above and below normal operations. Air manifold temperatures were varied by manually changing the temperature setting, causing the engine to increase or decrease water flow through the turbocharger jacket. Air manifold pressures were changed by increasing and decreasing combustion air flow to the engine. Engine efficiency was altered by manually forcing the computer to retain its sensed horsepower while the actual horsepower was changed. Ignition timing was adjusted manually to vary this operating parameter.

To evaluate the impact of torque and speed settings on the operating perturbations listed above, these engine parameters were perturbed at three different torque and speed operating regimes. This resulted in a total of 24 individual test runs during off-normal engine operations. The values in Table 3-4 represent the perturbed engine parameter values and the torque and speed settings for each test run. More detail regarding the off-normal test matrix is presented in the Test Matrix summaries in Appendix A. These include a description of each engine parameter that was perturbed during the tests, the level of perturbation relative to baseline (normal) operation, and a description of PEMS alerts or alarms that were evident during the tests.

Table 3-4. Off-Normal Engine Operating Conditions Tested

Operational Parameter/Alarm Condition		**Approximate Engine Speed/Torque Settings**		
		350 rpm / 94%	**280 rpm / 94%**	**350 rpm / 75%**
Efficiency (%)	High	105	107	107
	Low	93.8	94	93
Ignition Timing (degrees)	High	13.7	6.75	15.4
	Low	12.7	5.80	14.2
Air Manifold Temperature (^oF)	High	129	129	129
	Low	121	121	121
Air Manifold Pressure (psig)	High	19.8	14.5	15.5
	Low	18.4	12.9	14.5

Because no other engines at the host site were operating during the entire test period, ANR did not experience any difficulties operating at the desired set points, or intentionally upsetting engine operation. As detailed in Section 2.4.2, test runs were 21 minutes in duration after stable operating conditions were attained at the desired torque and speed setting. Immediately before starting a test, the engine components were perturbed so that either an alarm or alert was reported by the PEMS for that parameter.

The g/BHp-hr based results for off-normal operating conditions are summarized in Figures 3-9 and 3-10. Figure 3-9 shows the measured and predicted emission values during each test and Figure 3-10 summarizes the percent difference between measured emissions and predicted emissions for each parameter during each of the 24 off-normal operating tests. The charts also include engine speed and torque settings during the runs, and the engine operating parameter that was perturbed above or below normal. The test runs are not presented in chronological order, but are grouped according to the engine operating parameter that was perturbed. Additional detail regarding the individual test conditions, including RM measurements, PEMS predictions, and values for engine operating parameters is provided in Appendix B.

Air Manifold Pressure

Forced changes in combustion air manifold pressure had a significant effect on measured emissions of NO_x and THC, a small but measurable effect on emissions of CO, and no effect on CO_2 emissions as shown in Figure 3-9. At the three different engine operating set-points, emissions of NO_x averaged approximately 40 percent higher at low manifold pressures than during the high pressure tests. Emissions of CO and THC averaged approximately 11 and 17 percent higher, respectively, during tests when pressures were perturbed higher than normal.

Figure 3-9 shows that PEMS-predicted NO_x emissions were also higher during each of the low manifold pressure tests (Runs 36, 43, and 49). However, Figure 3-10 shows that percent differences between the predicted and measured NO_x emissions were highest during these tests. This indicates that the PEMS does respond to the manifold pressure changes, but predictions are less accurate as pressure decreases. During the high manifold pressure tests, the average difference was 19 percent, while at low pressure the difference averaged 5 percent.

The PEMS performance was similar with predictions of both CO and THC during the manifold pressure tests. Specifically, Figure 3-9 shows that PEMS-predicted emissions were higher during each of the high manifold pressure tests (as were the measured values), but Figure 3-10 shows that percent differences between the predicted and measured CO and THC emissions were highest during the low pressure tests. This indicates again that the PEMS does respond to the manifold pressure changes, but predictions are less accurate as pressure decreases.

Air Manifold Temperature

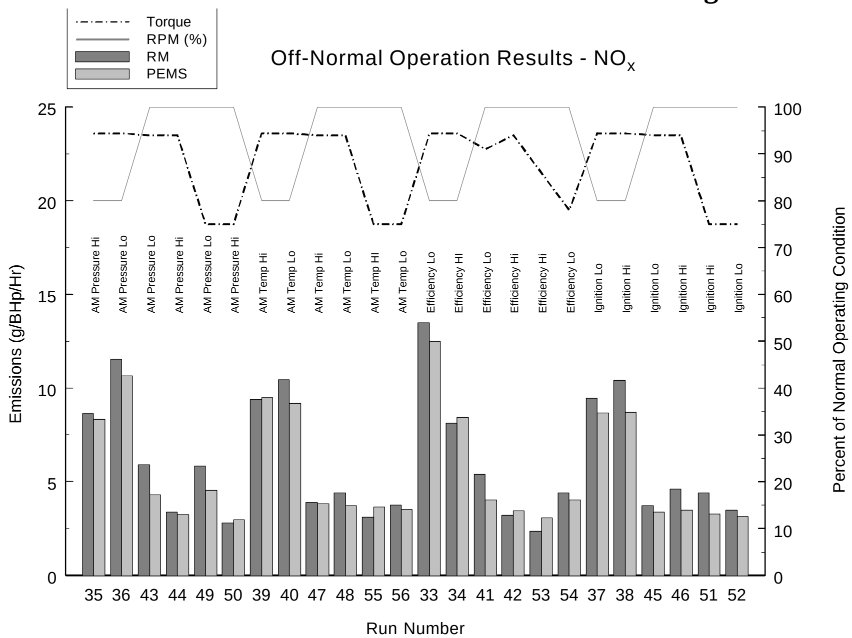
Perturbations to air manifold temperature had a small but measurable effect on emissions of NO_x, and insignificant effects on emissions of CO, THC, and CO_2 as shown in Figure 3-9 (Runs 39, 40, 47, 48, 55, and 56). At the three different engine operating set-points, measured emissions of NO_x averaged approximately 10 percent higher at low manifold temperatures than during the high temperature tests.

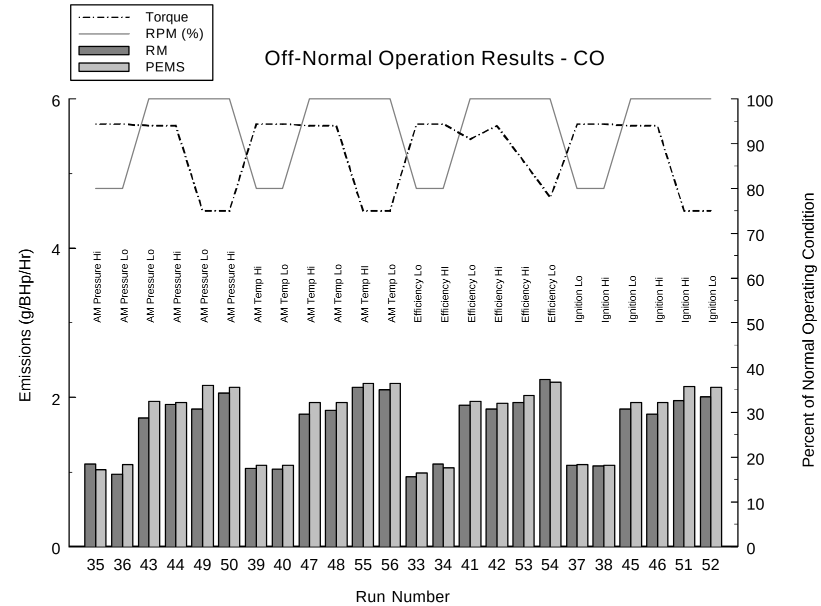
Figure 3-9 also shows that PEMS predictions did not respond to these small changes in measured NO_x and were consistent at high and low temperatures. This is further illustrated in Figure 3-10 where percent differences from the reference method values are highest during the low temperature tests with an average difference of 11 percent.

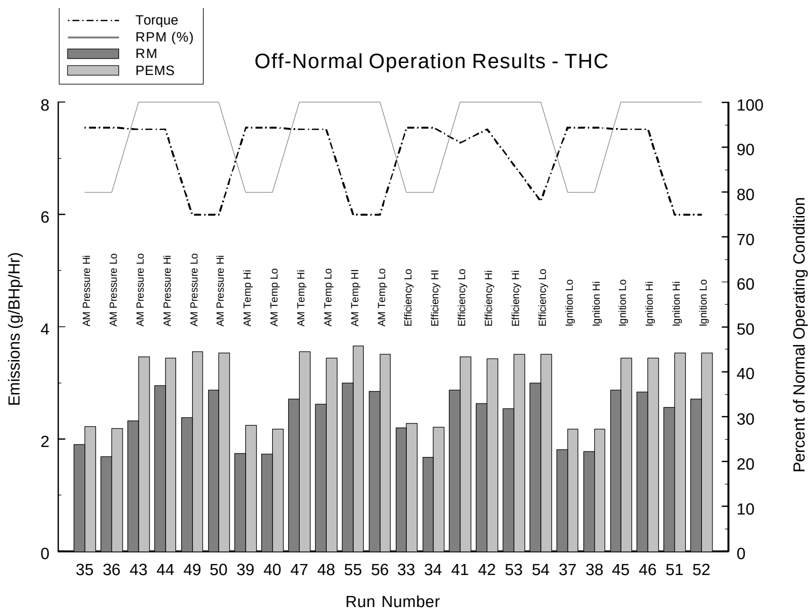
Engine Efficiency

Perturbations to engine efficiency resulted in measured NO_x, THC, and CO_2 emissions that were consistently higher during the low efficiency tests. Measured emissions of CO were not affected by the efficiency perturbations. Changes in engine efficiency had the greatest effect on NO_x emissions with rates averaging 42 percent higher during the low efficiency tests.

Figure 3-9. Off-Normal Test Results







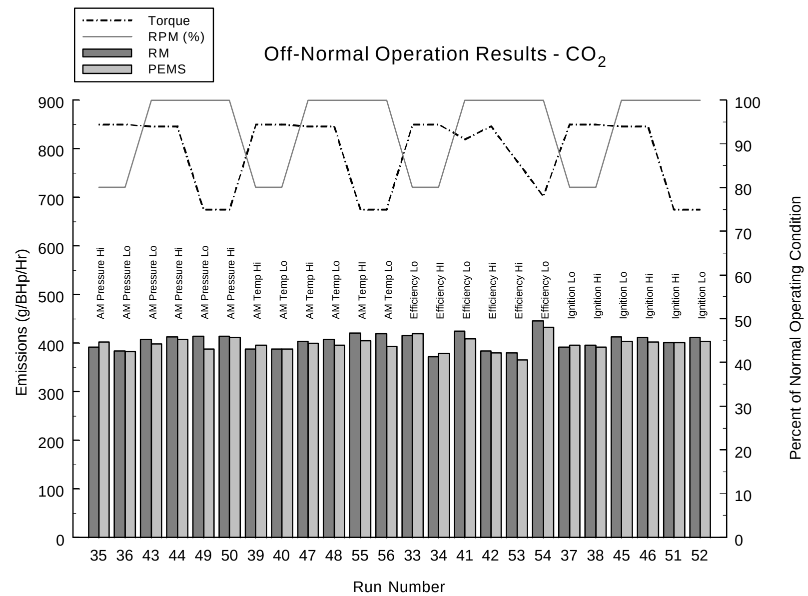
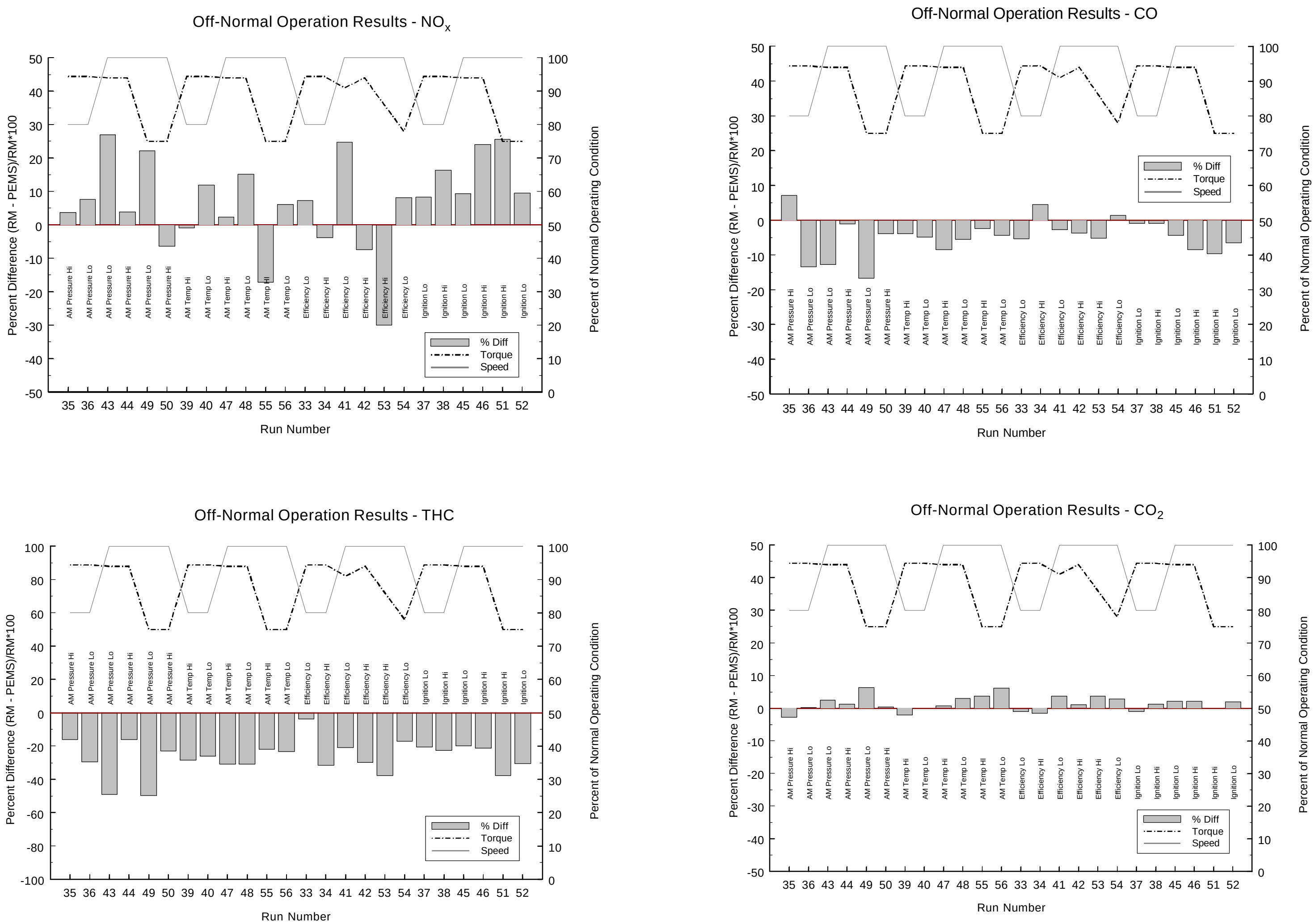


Figure 3-10. Off-Normal Test Results as Percent Difference



PEMS performance for NO_x emission rate predictions was erratic during these tests. Figure 3-10 shows that differences ranged from approximately -3 to -30 percent during high efficiency operation (i.e., predicted NO_x was greater than measured), while differences ranged from +8 to +23 percent during low efficiency (i.e., predicted NO_x was less).

Predictions of THC were less erratic but still variable during these runs with differences ranging from approximately 4 to 38 percent. PEMS THC predictions were consistently closer to the reference method values during the low efficiency perturbations. The PEMS tracked changes in CO_2 emissions very closely and all runs were within 5 percent of the reference method values.

Ignition Timing

Changes in the engine ignition timing had a small but measurable effect on measured NO_x emissions with higher timing settings resulting in slightly higher emissions. While measured emissions were approximately 1 g/BHp-hr higher during each of the high timing tests, NO_x emissions predicted by the PEMS increased by only 0.04 to 0.14 g/BHp-hr. As shown in Figure 3-10, predicted NO_x emissions during these three tests were approximately 14, 23, and 24 percent lower than measured. The ignition timing perturbations had little or no effect on measured emissions of THC, CO, and CO_2.

The following is a summary of the findings of the off-normal engine operation tests:

- PEMS predictions of CO and CO_2 emissions were within approximately 15 and 5 percent, respectively, of the reference method values during these tests.

- PEMS predictions of NO_x emissions are less accurate during periods of low air manifold pressure (19 percent difference), and low air manifold temperature (11 percent difference).

- PEMS predictions of NO_x emissions are less accurate during periods of abnormally high or low engine efficiency.

3.4 PREDICTION CAPABILITIES DURING SENSOR DRIFT/FAILURE

Sensor failure or drift was simulated by changing the electronic signal received by the PEMS from the sensors important to PEMS functions. These tests were conducted to evaluate the PEMS ability to respond to failure or drift of one or more sensors, rather than changes to engine operation. The sensors perturbed during this series of tests included ignition timing, engine efficiency (fuel flow sensor), air manifold temperature, and air manifold pressure. The sensors were perturbed by intercepting the sensor output signals received by the PEMS, and electronically adjusting the signals using the control inhibit mode of operation that is built into the engine operating software. The control inhibit mode is available because engine operation can be affected by these sensor signal perturbations. Separate test runs were conducted for each sensor while simulating sensor drift both above and below normal levels. At the beginning of each test, baseline data were collected for a 10-minute period during steady state engine operations. For all of these tests, steady state operation is defined as normal operation at speeds of around 320 rpm and loads of approximately 85 percent torque. The 10-minute baseline period was followed by a series of stair-step sensor perturbations to levels that reached parameter alert and/or alarm levels (while maintaining steady engine conditions). Ten minutes of emissions data were collected during each step perturbation resulting in test durations of up to 40 minutes depending on the number of step perturbations achieved.

3.4.1 Single Sensor Perturbations

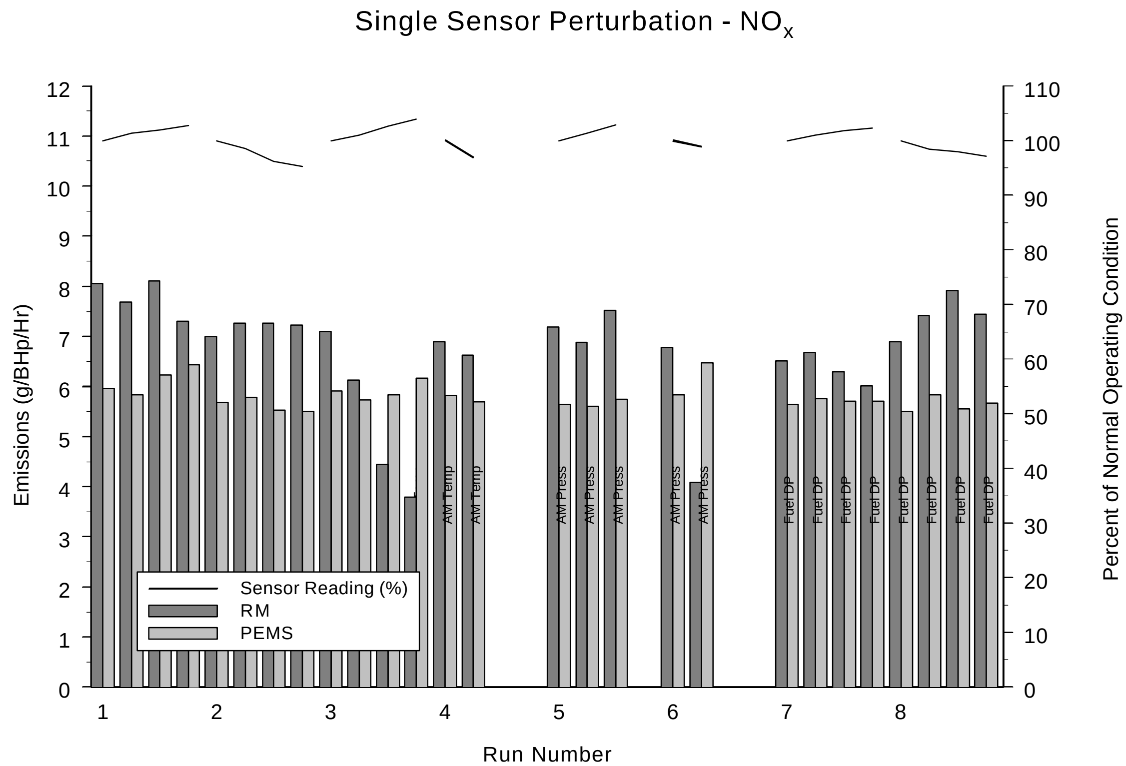
Test runs 1 through 8 constitute the eight single sensor perturbation tests. The tabular summaries for these runs in Appendix A include the date and times for the runs, and the sensor values for each perturbation step. The first ten minutes of each run were at steady state operations. From that condition, three steps of sensor perturbation were attempted while collecting ten minutes of test data at each level. Sensor alarm levels were exceeded for each test conducted.

The manifold pressure tests were stopped after only one perturbation below normal and two levels above normal. The PEMS incorporates a narrow alert and alarm band for this parameter because manifold pressure significantly affects engine performance. During run 4, only one level of manifold temperature perturbations below normal was performed because the engine was beginning to overheat. Three step perturbations were achieved during each of the other tests conducted. Each of these tests was 40 minutes in duration.

Test results for PEMS predictions of NO_x and THC during single sensor perturbations are summarized in Figures 3-11 and 3-12. Reference Method data and PEMS predictions of CO_2 and CO are not included in the plots because the sensor perturbations did not affect emissions of these compounds. Furthermore, the PEMS predictions for these pollutants were essentially unchanged by these perturbations because the sensors perturbed affected the engine's combustion process in a negligible way for these specific pollutants. This type of phenomenon is reported by ANR to be engine specific.

The plots display the recorded values (Figure 3-11) and the percent difference (Figure 3-12) between measured and predicted emissions for NO_x and THC during each sensor perturbation step. The plots also show the sensor output levels during each step of perturbation as a function of sensor full scale using the right axis. The measured and predicted emission rates for all four pollutants at each test point are presented in tabular form in Appendix B.

Figure 3-11. Single Sensor Perturbation Results



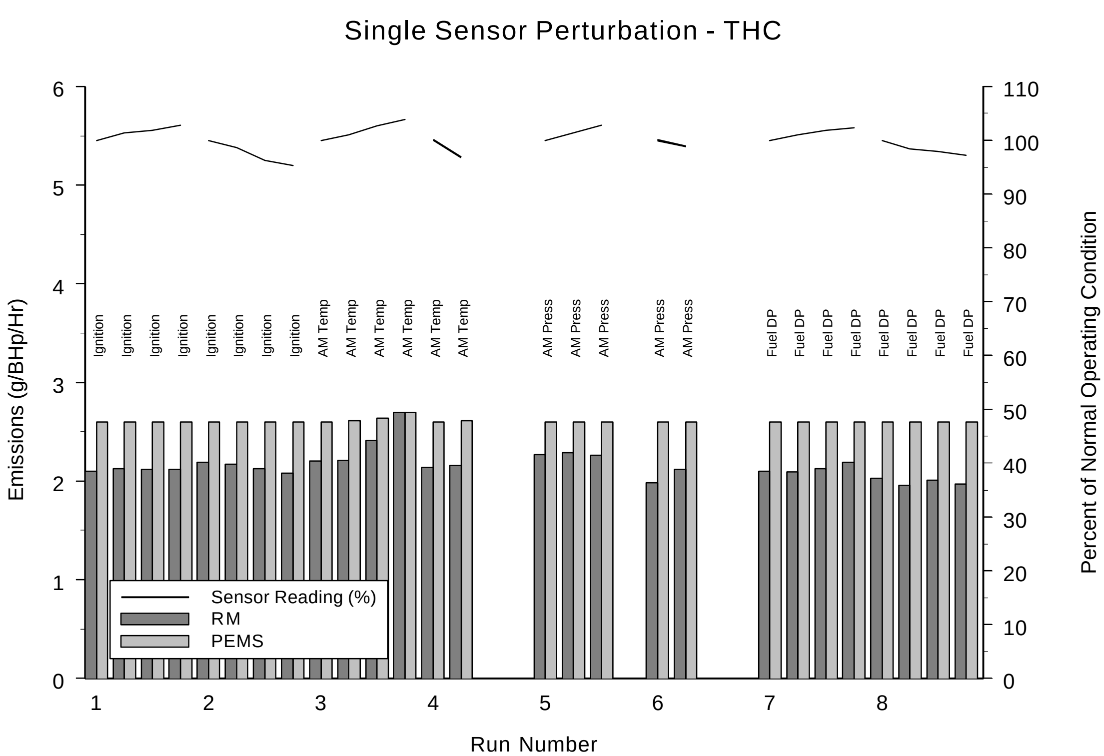
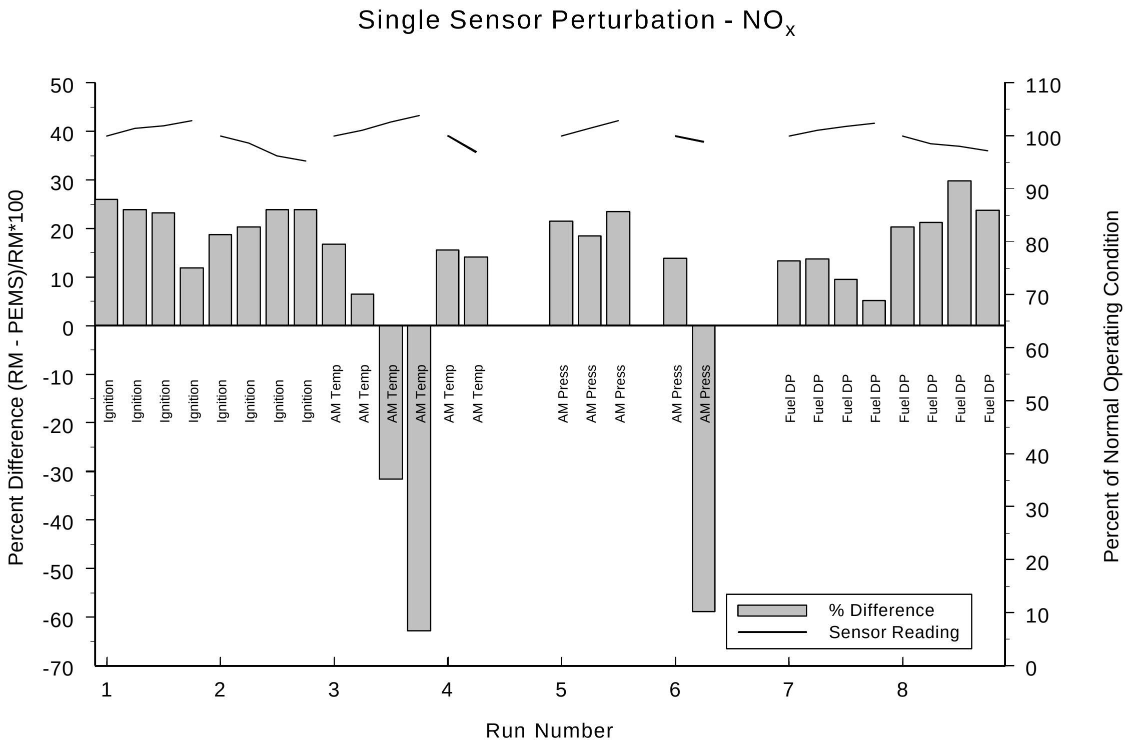
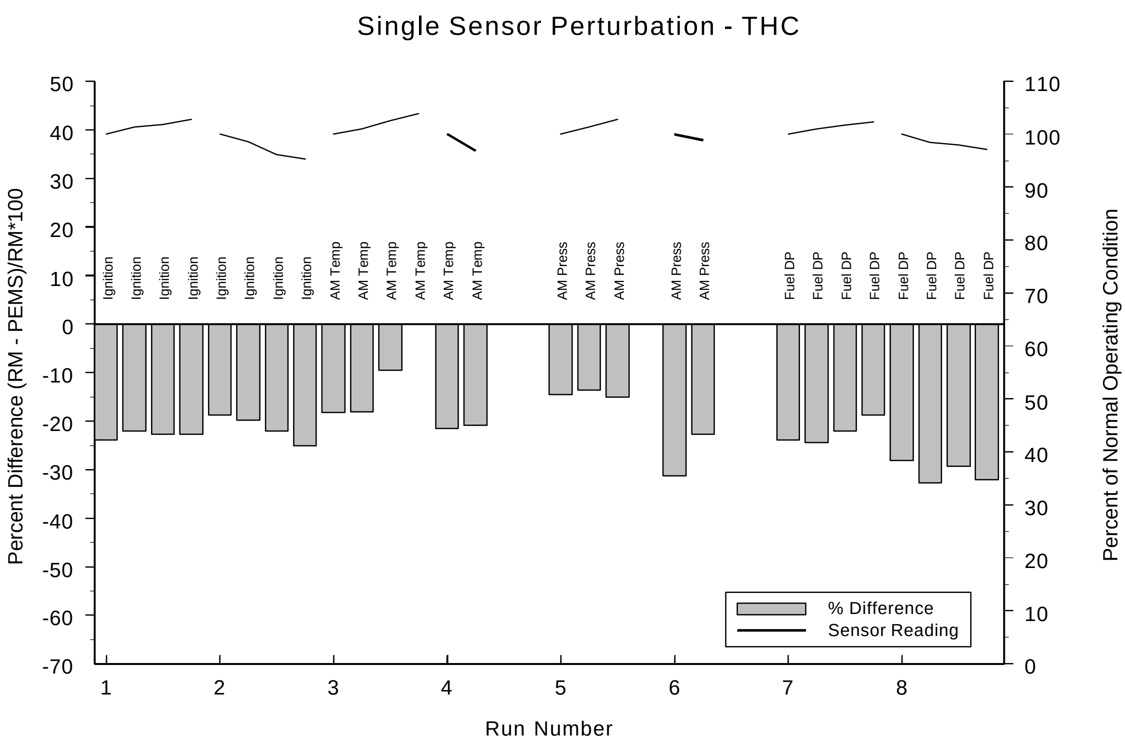


Figure 3-12. Single Sensor Perturbation Results as Percent Difference



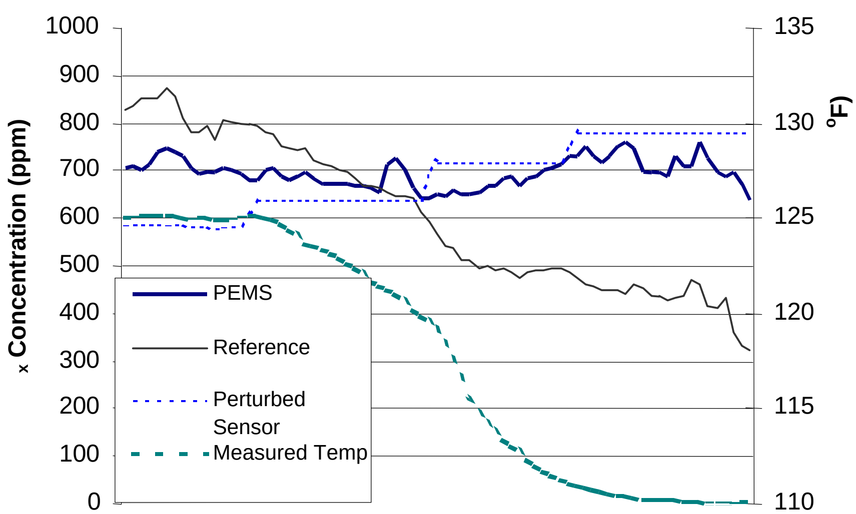


Perturbations to ignition timing and fuel DP sensors had a minimal effect on engine operation and measured emission rates. During these tests, PEMS emission predictions were steady and, with the exception of THC, were within 25 percent of measured NO_x emissions, 10 percent of CO, and 8 percent of the measured CO_2 emissions during all of the perturbation steps simulated.

Air manifold temperature and pressure sensor perturbations did affect measured NO_x emissions. For air manifold temperature and pressure measurement, the engine is equipped with redundant sensors. The redundant values were essentially the same during normal baseline engine operations, verifying proper sensor performance. However, during sensor drift or failure, the PEMS is designed to default to the sensor value that results in the higher NO_x emission rate prediction - regardless of which sensor is correct. Specifically, when one of the air manifold temperature sensors drifts or fails, the PEMS defaults to the higher signal. When one of the air manifold pressure sensors drifts or fails, the PEMS defaults to the lower signal. These defaults both result in higher predicted NO_x emission rates.

Test results show that when a temperature sensor was perturbed high as during Run 3, the PEMS and the Accol software recognized the signal and engine cooling was increased. The redundant sensor was then monitoring the manifold temperature, which dropped dramatically. Subsequently, NO_x emissions as determined by the reference method also dropped, but not the PEMS predictions (the PEMS is designed to predict conservatively in this case). Figure 3-13 shows measured and predicted NO_x concentrations during Run 3 in relation to the measured manifold temperature. The perturbed temperature sensor values are also plotted.

Figure 3-13. NO_x Emissions at High Air Manifold Temperatures (Run 3)



Conversely, when a temperature sensor was perturbed low as during Run 4, the PEMS simply defaulted to the other sensor which was still measuring temperature. In this case, the PEMS (and Accol controller) and the engine remained unchanged. This series of tests supports ANR's claim that, where redundant sensors are in place and on sensor drifts or fails, the PEMS defaults to the signal that results in the higher NO_x emission rate prediction as was the case in Run 3.

Changes in air manifold pressure can have a significant effect on engine operation and therefore the alert and alarm levels built into the PEMS are very restrictive. No significant changes in PEMS NO_x predictions were observed during Run 5 when a pressure sensor was perturbed high, although the reference method NO_x did show a slight increase in emissions. During Run 6, when the pressure sensor was perturbed low, the engine controller recognized this drift and manifold pressure increased to a point where the engine was nearly shut down. As shown in Figure 3-14, during the last 5 minutes of this test measured NO_x emission dropped dramatically with the increased pressure, but the PEMS predicted higher NO_x values, again reporting conservatively. Several tests like these nearly tripped the engine so they were aborted prematurely and did not continue over the full 40-minute duration.

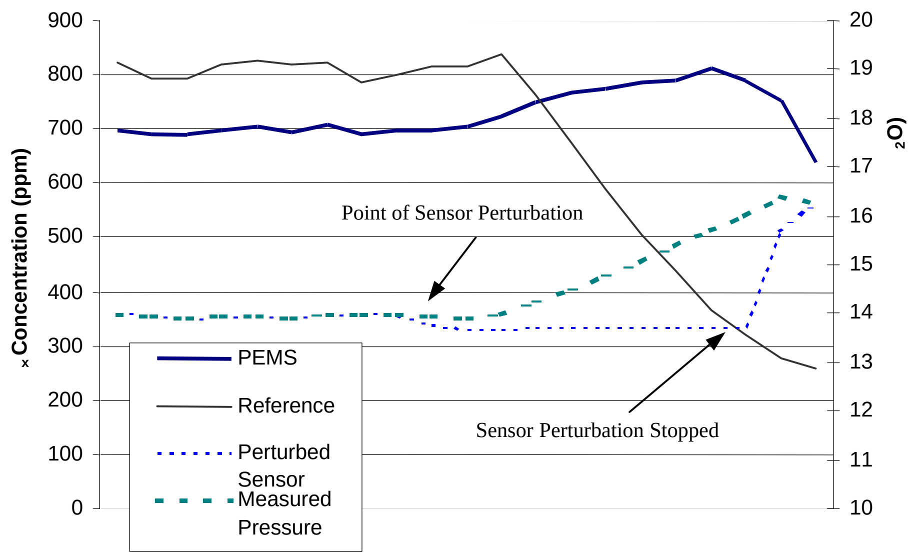
The following summarize the findings of the single sensor perturbation tests:

- The single sensor perturbations had little or no effect on emissions other than NO_x. NO_x predictions during the perturbations were erratic.

- Consistent with the other tests conducted, PEMS predictions of THC were generally 20 to 30 percent higher than measured emissions.

- Where redundant sensors were tested, the PEMS defaulted to the sensor that predicts NO_x emissions conservatively according to PEMS design.

Figure 3-14. NO_x Emissions at Reduced Air Manifold Pressure (Run 6)



3.4.2 Double Sensor Perturbations

Test runs 9 through 18, 31 and 32 comprise the 12 double sensor perturbation tests. The tabular summaries for these runs in Appendix A also include the dates and times for the runs, and the sensor values for each perturbation step on both sensors. Consistent with the single sensor tests, the first ten minutes of each run were at steady state operations. From that condition, three steps of sensor perturbation were attempted while collecting ten minutes of test data at each level. Sensor alert or alarm levels were exceeded for both sensors during each test conducted.

As was the case during the single sensor perturbation tests, many of these tests were stopped prior to achieving all three perturbation steps. Tests were stopped early when both sensors had reached alarm levels after only two steps, or when the engine was misfiring, overheating, or approaching stall conditions. These conditions were most prevalent during runs 11 through 14, 16, and 32 when air manifold pressure and/or manifold temperature sensors were perturbed.

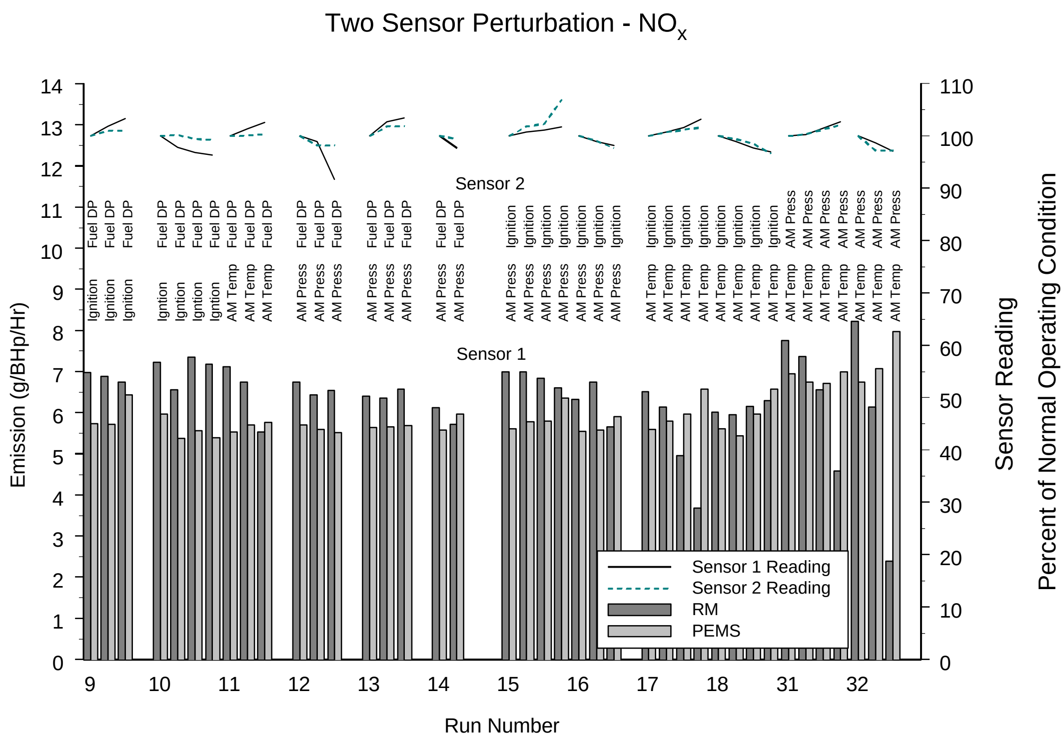
Results of the double sensor perturbation tests are illustrated in Figures 3-15 and 3-16. Numeric results of each test point are presented in tabular form in Appendix B. In general, results of these tests are similar to the single sensor tests in that only air manifold temperature and pressure perturbations had significant effects on measured NO_x emissions. Measured THC, CO, and CO_2 emissions were not significantly affected by any of the perturbations with one exception. During Run 32 when manifold temperature and pressure sensors were both perturbed low, measured THC emissions increased from approximately 1.8 to 2.7 g/BHp-hr. The PEMS did not respond to this change in emissions. Emissions of CO and CO_2 were steady throughout these tests and PEMS predictions of these two pollutants were very accurate with percent differences from the reference method values well within 10 percent.

Because the engine is equipped with redundant air manifold temperature and pressure sensors, combined perturbations to these sensors had a similar effect on actual NO_x emissions as was observed earlier during the single sensor tests. Specifically, when one redundant sensor was perturbed, the Accol software and the PEMS consistently defaulted to the sensor input value that resulted in higher NO_x predictions. This effect was magnified during Run 32 when both the pressure and temperature redundant sensors were perturbed and predicted NO_x emissions were actually 234 percent higher than the measured value. This result may not be reliable because this test was not conducted under normal engine operations and had to be aborted because of stress on the engine and the possibility of engine trip off. During each of the tests not involving redundant sensors, the PEMS consistently predicted NO_x emission rates within 10 to 25 percent of the reference method values.

The following summarize the findings of the double sensor perturbation tests:

- The double sensor perturbations had little or no effect on measured emissions other than NO_x where predictions during the perturbations were erratic.
- PEMS predictions were representative of CO and CO_2 measurements.
- Consistent with the other tests conducted, PEMS predictions of THC were generally 20 to 30 percent higher than measured emissions.

Figure 3-15. Double Sensor Perturbation Results



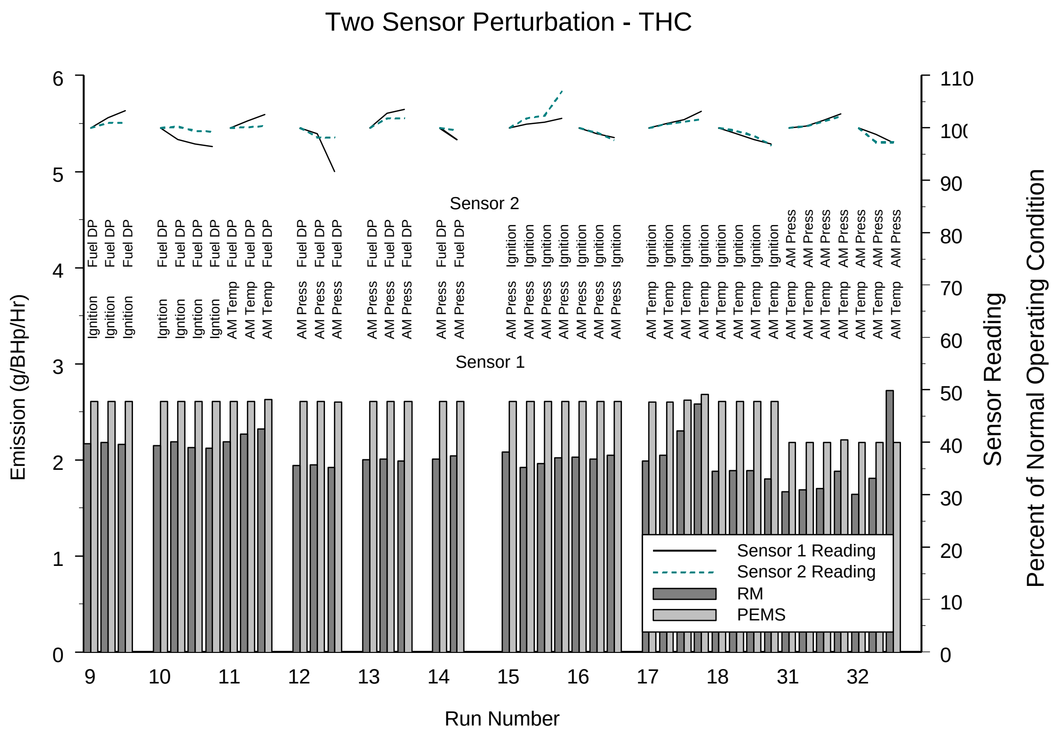
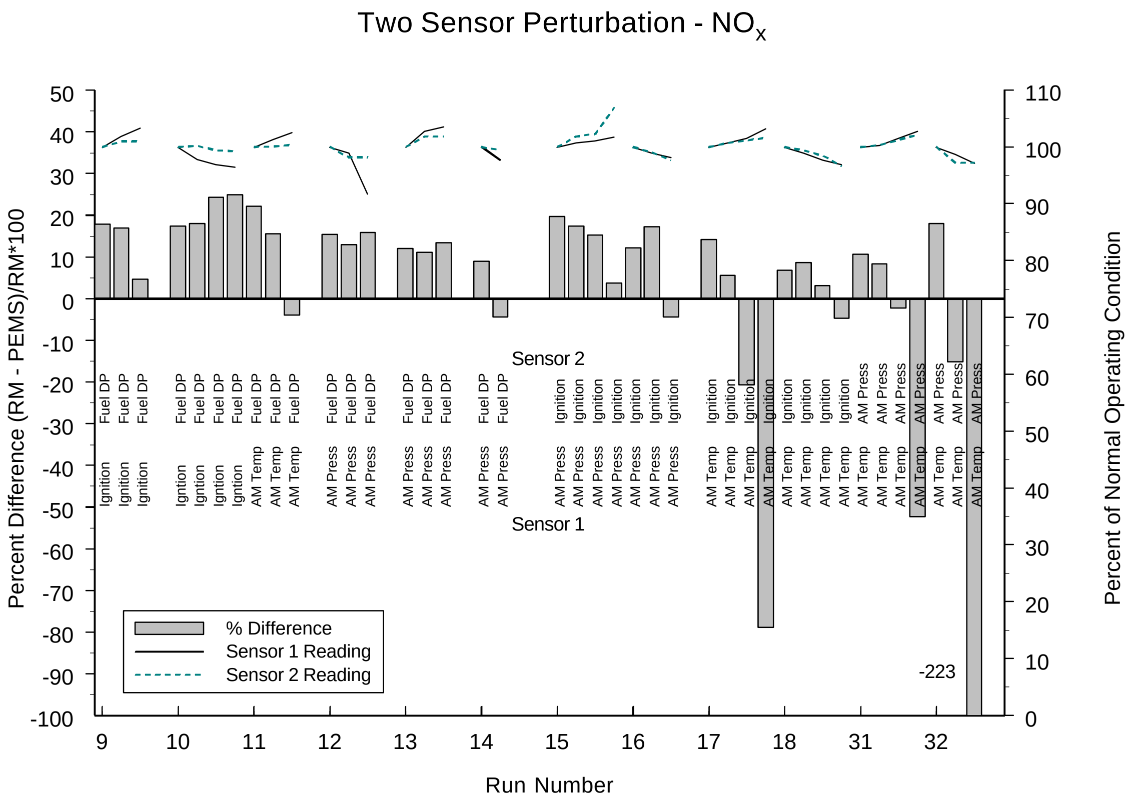
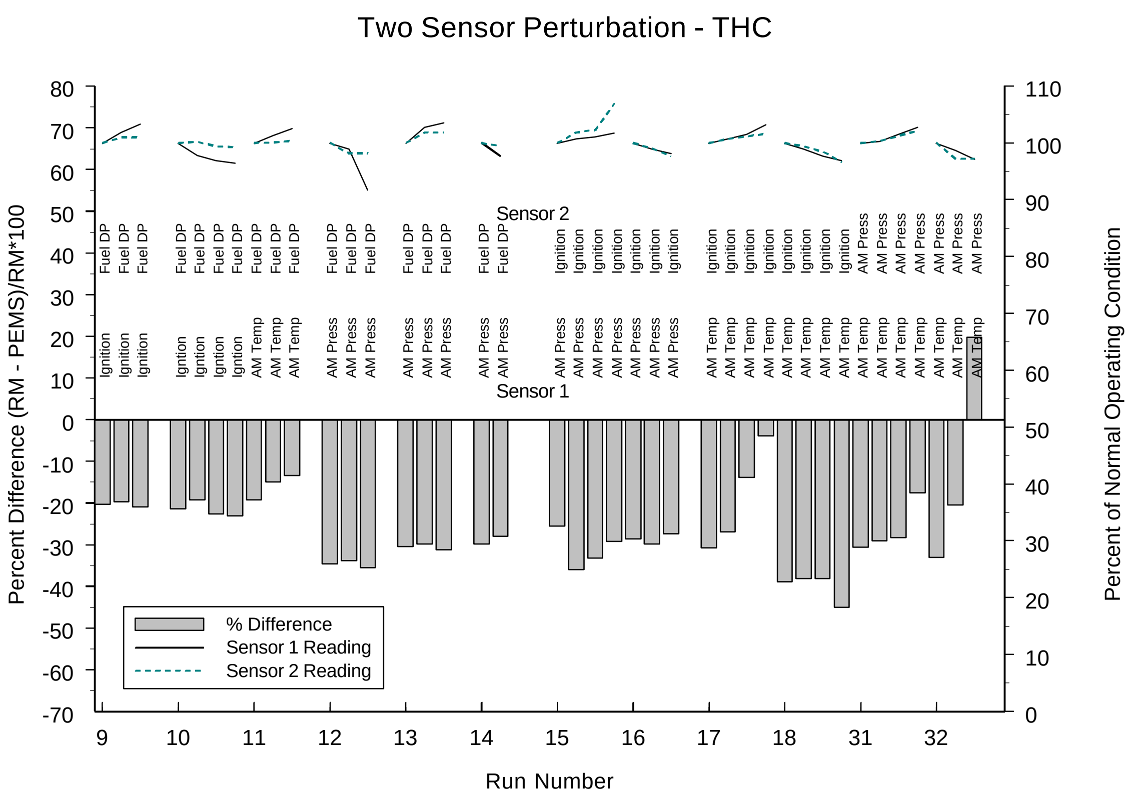


Figure 3-16. Double Sensor Perturbation Results as Percent Difference





- When redundant sensors were tested, the PEMS defaulted to the sensor that predicted NO_x emissions conservatively according to PEMS design.

3.5 PEMS DIAGNOSTIC CAPABILITIES

The alert and alarm levels of each of the PEMS key sensors can be set at whatever level the operator desires. The operator can also select a desired delay time before alerts or alarms are reported by the PEMS. This system was set up so that a sensor or engine parameter needed to exceed the designated alert or alarm level for 15 consecutive seconds before the PEMS reported the occurrence. The alerts and alarms are designed and set to notify operators of engine malfunction or failure, sensor malfunction or failure, or emissions exceedances. During this test program, emission rate alerts or alarms were not designated in the PEMS. Alert and alarm levels were specified for each of the sensors and engine variables tested as defined in Table 2-4.

Data collected during the off-normal engine operation tests and the sensor drift tests were used to assess how well PEMS provides diagnostic information that engine operators can use to identify and rectify engine operating and sensor problems. These data were used to assess PEMS ability to warn of poor engine performance and subsequent emission increases. PEMS alarms and alerts recorded under the sensor failure analyses described in Section 3.3 are used to qualify how well PEMS alerts operators to the existence of failed sensors, or the possibility that a sensor is drifting significantly.

During the sensor perturbation tests, sensor outputs were manually adjusted to the alert and alarm levels designated during PEMS setup activities. No alerts or alarms were observed prior to adjusting sensor values past the set levels. During the sensor testing, alerts and alarms were reported only for the perturbed sensors because actual engine upsets did not exist. For parameters for which redundant sensors are not in place, the PEMS does not provide a means for determining whether the alert or alarm is a result of failed sensor(s) or engine component failure.

However, where redundant sensors are used (air manifold pressure and temperature, and fuel dP), engine operations are upset by failed or drifting sensors. As described earlier, the PEMS defaults to the higher temperature sensor and lower pressure sensor in order to predict NO_x emissions conservatively. When sensor failure or drift occurs, the engine control program automatically increases engine cooling capabilities and/or increases manifold pressure because it is responding to the failed or drifting sensor signal. This situation can result in many different alerts and alarms as the engine approaches shut down. The PEMS includes alerts and alarms for both the primary and redundant sensors. Therefore, where redundant sensors are used it is very easy for the operator to determine if the alert or alarm is caused by sensor drift or failure (only one sensor will alert) or an engine malfunction (both sensors will alert).

In summary, the PEMS contains comprehensive alarm/alert functions that provide diagnostic capability. At the test site, as at many compressor stations, engine sensor alerts and alarms may already be implemented in the station control system and, in such cases, the PEMS may not provide additional engine sensor alarm/alert capability. However, the use of redundant sensors by the PEMS does enhance diagnostic capability over what would otherwise be available because it allows the operator to quickly determine if an alarm is the result of a failed sensor or an engine malfunction. In addition, the PEMS provides capability to readily assess and track changes in engine operations in terms of emissions.

4.0 DATA VALIDATION AND QUALITY

4.1 DATA QUALITY

The data presented in the appendices of this report represent results of each of the tests conducted during this study. All test runs performed are reported here. With the one exception discussed below, all of the data are classified as valid based on the following two criteria:

1. The data quality goals were met, and
2. The desired engine operating set points were achieved.

As explained in Section 2.3.1, PEMS ppmvd concentration data for all gases from the first RA test run were not included in the RA calculations due to a short period of suspiciously high oxygen content measured by the ANR test team. The data from the test are reported, but not used in the overall RA determination for units of ppmvd. This problem did not affect the predicted g/BHp-hr values for the first RA test run.

EPA Reference Methods were followed to conduct each of the tests, and the Center used the calibration procedures and data quality checks specified in each method to assess data quality. The three data quality parameters assessed were completeness, precision, and accuracy.

To assess accuracy, analyzer calibration error (linearity) and system bias were determined in accordance with the appropriate reference methods. The results of these quality control tests demonstrate that the verification test results meet the requirements of the EPA test methods. Linearity was checked at the beginning of each day of testing by introducing a suite of calibration gas standards (certified as EPA Protocol 1) directly to the analyzers and recording analyzer response. System bias was checked before and after each test run by introducing the zero and mid-span gases to the sampling system at the probe and recording the system response. Results are presented in Appendix C and summarized in the first two columns in Table 4-1.

Table 4-1. Summary of Reference Method Calibration Results (% of Span)

	Calibration Error		System Bias		Drift	
Parameter	**Highest Measured**	**Specified Objective**	**Highest Measured**	**Specified Objective**	**Highest Measured**	**Specified Objective**
NO_x	0.43	2.0	1.32	5.0	1.17	3.0
CO_2	0.60	2.0	1.80	5.0	1.85	3.0
CO	0.79	2.0	2.68	5.0	1.86	3.0
THC[a]	0.47	5.0	2.55	5.0	2.64	3.0
O_2	1.72	2.0	3.92	5.0	1.96	3.0

[a] Method 25A specifies that calibration error checks be conducted through the entire sampling system only. For additional quality control, the calibration procedures of Method 6C were followed for THC during this test.

All calibration error tests were below ± 2 percent of span for each analyzer used during each run. In addition, the system bias tests conducted before and after each test run were all well under the method requirement of ± 5 percent of span.

To evaluate measurement precision, sampling system drift was calculated using the bias checks conducted before and after each test. The system drift is defined as the difference between the final and initial system response divided by the span value. Calculated system drift test results are also presented in Appendix C and summarized in the last column in Table 4-1. The results show that the drifts were less than ± 3 percent of span for all parameters during each of the 56 tests, as specified in the reference methods.

The completeness goals stated in the test plan specified that 100 percent of the relative accuracy tests, 100 percent of the sensor perturbation tests, and 85 percent of the off-normal engine operation tests would be used to evaluate the PEMS. Because the data quality indicator goals were met for each test run as stated above, these completeness goals were also met. The test plan originally specified that testing would evaluate sensor perturbations to five sensor types. However, because this engine was not equipped with an exhaust manifold pressure sensor, only four sensors were evaluated. Likewise, this reduced the number of double sensor perturbation tests from 20 to 12. The final completeness values are 100 percent for the RA tests as mass rate and 91 percent for concentration, and 100 percent for both the off-normal and sensor perturbation tests.

No major problems were encountered obtaining the desired test conditions for the off-normal engine tests. All the tests proposed in the plan were conducted and included in the verification. Although all the tests conducted during sensor perturbations are included in this evaluation and are considered valid, several of these tests were aborted before the entire 40 minute test (and three step perturbations) could be completed. Specifically, test runs involving perturbation to the redundant air manifold temperature and pressure sensors caused engine misfiring and efficiency alerts that precluded finishing the entire tests. The tests cut short included Runs 4, 6, 11, 14, 16, and 32. However, the shortened runs did provide sufficient data to evaluate the PEMS consistent with overall test goals.

4.2 DATA QUALITY ASSESSMENT

After completion of the verification testing, the Center conducted an internal Technical Systems Audit (TSA) and Audit of Data Quality (ADQ). The audits were conducted by SRI QA staff on November 16, 1999 at the Center and assessed data reduction procedures, data archival, and project quality control activities. Conduct and documentation of all were satisfactory to meet the project goals.

5.0 ANR COMMENTS

As discussed in Section 3.1 of this report, a disparity in emissions measurements was noted between the two test contractors regarding both the initial PEMS set-up and subsequent verification testing. The most significant disparity was found in the THC emissions measurement; however, differences between both reference vans for NO_x, CO, and CO_2 emissions were reported as well. In our experience, this happens frequently whenever testing is performed on the same engine by different emissions testing contractors. In this specific verification testing program the ANR PEMS was well within the EPA Performance Specifications for NO_x, CO, and CO_2, but our concern is for those times when the differences are greater. In fact, this did occur with the THC measurement, which is discussed in detail by SRI in Section 3.1.

ANR believes the cause of these differences is not that the reference vans are poorly equipped or that the test technicians lack training or expertise but rather, that the protocols utilized for emissions testing are not flexible enough to account for the inherent limitations in the test equipment itself. This illustrates the importance of establishing more of a non-prescriptive regulatory policy with regard to emissions testing. In support of this, ANR recommends that the following points be strongly considered by EPA and other regulatory agencies when involved in the verification of air emissions from engines:

1. Recognize that measurements between different reference test vans will inherently and not uncommonly vary and allow for such variance when setting up the acceptance criteria.

2. Wherever possible, utilize the same equipment, operator, and testing methods when conducting periodic acceptance testing on an engine. This will be especially important when measured emissions are low because the accuracy of the test equipment does not improve with decreasing absolute emissions measurements.

3. Implement more flexibility in existing air emissions test protocols to accommodate issues such as: DNPH shift by NO_x, corrections for flow measurement in pulsing flow fields, approving new technologies to more accurately and cheaply measure emissions (e.g., standardization of FTIR spectra, Celanese method for aldehydes).

6.0 REFERENCES

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U.S. Environmental Protection Agency. *Reference Methods 3A, 6C, 7E, 10, 19, and 25A Determination of Carbon Dioxide and Oxygen, Sulfur Dioxide, Oxides of Nitrogen, Emission Rate, and Total Gaseous Organic Concentration, respectively.* Code of Federal Regulations, Title 40, Part 60, Appendix A, 1999.

U.S. Environmental Protection Agency. *Example Specifications and Test Procedures for Predictive Emissions Monitoring Systems.* Document can be obtained at: www.epa.gov/ttn/emc/cem.html. Posted 1/25/96.

U.S. Environmental Protection Agency. Code of Federal Regulations, Title 40, Part 60, Appendix C, and Part 75, Appendix E. 1999.