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ON-BOARD HEAVY-DUTY TRUCK MOBILE EMISSION TESTING IN SUPPORT OF MOBILE SOURCE EMISSION INVENTORIES AND ON-BOARD EMISSIONS FACTOR FOR DIESEL BUS

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AQMP	1991 South Coast Air Quality Management Plan
CARB	California Air Resources Board
CBD	Central Business District
CEM	Continuous emissions monitoring
EPA	Environmental Protection Agency
ETF	Emissions Testing Facility
I/O	Input/output
LACMTA	Los Angeles County Metropolitan Transportation Authority
NDIR	Non-dispersive infrared
OCTA	Orange County Transit Authority
SIP	State Implementation Plan
TCMs	Transportation control measures
UPS	Uninterruptible power supply

SECTION 1

INTRODUCTION

The objective of this project was the development and testing of on-board emissions measurement capability for heavy-duty vehicles utilizing a new unique measuring technique under Contract #92-924, On-Board Heavy-Duty Truck Mobile Emission Testing in Support of Mobile Source Emission Inventories for the California Air Resources Board (CARB). Follow-up testing was funded by the Environmental Protection Agency (EPA) under Contract #68-D2-0063, On-Board Emissions Factors for a Diesel Bus. The work was conducted between August 1993 and February 1995.

The technology approach is presented in Section 2. It is based on extensive experience Acurex Environmental gained while testing utility power plants and other emission sources requiring on-line emissions testing. Section 3 discusses how the stationary-source testing technology was adapted to measure emissions from a diesel bus outfitted with special sensors and the equipment that was proposed and used during the tests. It should be understood that this project was a concept demonstration and was not intended to result in a measurement apparatus that would be routinely utilized to measure emissions from diesel trucks, buses or tractors. Commercial equipment satisfying that criteria would have to be substantially reduced in size, requiring significant commercial product development effort. Section 4 presents the various test plans and Section 5 describes tests that were carried out. Section 5 discusses, in particular, many of the difficulties that were encountered during the tests resulting in the need to repeat the first chassis dynamometer test at the Los Angeles County Metropolitan Transportation Authority (LACMTA). Section 6 presents test data evaluations and results. Section 7 presents recommendations for further development of the system and further evaluation of the collected test data. Appendix A contains the technical paper presented at the CRC On-Road Vehicle Emissions Workshop at the Hyatt Islandia, San Diego, CA in April 1995 and Appendix B and C contain test data collected during the chassis dynamometer and on-road testing, respectively.

During the data analysis, we were able to successfully correlate the emission measurements from the Acurex Environmental system with those from the LACMTA system, despite some instrument errors that occurred with the Acurex Environmental system. There were problems both with the air flow measurement and with the calibration and response time of the NO_x analyzer. This made it difficult to directly compare the data from these two systems. However, we were able to develop adjustment factors for the flowrate and the NO_x measurement which overcame these errors to produce results that agreed very well with the results from the LACMTA system. Further work needs to be done to improve the flow measurement technique and to optimize the emissions analyzers. These findings are discussed in detail in Sections 5 and 6.

SECTION 2

MEASUREMENT TECHNOLOGY

2.1 TECHNOLOGY BENEFITS

Knowing the overall emissions inventory in a particular region (such as the South Coast Air Basin) is an important economic and air quality management consideration. As more transportation control and other emission reduction measures are implemented, understanding the baseline emissions and potential reductions becomes critical to the success of these measures. Projections of emission reductions from transportation control measures (TCMs) are at best modeled and rarely validated with actual experience. Because implementing the most cost-effective emission reduction measures is important, it is essential that emission reductions be quantified accurately. Models alone are not adequate for this task. The uncertainty in transportation control/emission inventory models often exceeds the emission reductions from smaller control measures such as enforcing the diesel truck speed limit. Determining actual emission reductions would help identify the most effective control measures that could be achieved at the least cost to the public. Additionally, having a clear understanding of the most cost effective control measures can enhance flexibility and minimize detrimental impacts on industry.

This project's goal was to identify significant emission benefits for the South Coast Air Basin by developing a measurement technique to quantifying on-road emissions from trucks. Quantifying on-road emissions addresses several of the control measures in the 1991 South Coast Air Quality

Management Plan (AQMP[1]). Appendix IV-C of the AQMP covers mobile source emission control measures. Included as mobile source reductions are emissions standards, alternative fuel use, and aerodynamic improvements related to heavy-duty trucks. Appendix IV-E of the AQMP lists transportation and land use measures. Under the category of truck dispatching, rescheduling, and rerouting, this project would help quantify the emissions benefit for measures such as pricing pollutants per ton-mile and enforcing the speed limit.

Measuring test vehicle emissions over a number of duty cycles appropriate for the particular test vehicle and engine would quantify actual emissions. The range of measured in-use emissions results across all duty cycles could be compared with the in-use emissions as predicted by ARB modeling. Furthermore, the relative contribution of operation in each duty cycle to the total South Coast Air Basin inventory could be estimated, and the estimate used to calculate a weighted average of the measured emissions. This result could be more appropriately compared with the in-use emissions as predicted by ARB models, which are intended to represent statistically average emissions across all engines and duty cycles within each weight class.

With data from this project, the potential reductions that could be achieved with operational restriction measures, some of which are included in the State Implementation Plan (SIP), could also be evaluated. Specifically, this would involve testing over a period of several days, where the reductions achieved from one potential measure would be evaluated each day. The operating restrictions that have been suggested and can be expected to impact emissions include strict enforcement of speed limits; no extended idling for waiting, loading, and unloading; and mandated installation of aerodynamic drag-reducing devices on trucks.

The data would also provide a relationship between on-road emissions and truck laden weight. This correlation would be useful because if it is found that increasing the load per vehicle

[1] The 1994 Final SCAQMP has been released since this project was performed. Appendix IV-B of the 1994 AQMP covers mobile source emission control measures. Appendix IV-C of the 1994 AQMP lists the transportation and indirect source control measures.

does not proportionally increase emissions, it would be beneficial to maximize the load per truck where possible as compared to using two trucks each hauling less weight.

Potential emission reductions from TCMs for trucks would reduce emissions by 5 to 15 percent for affected vehicles. This translates into 1,000 tons per year of NO_x if 10 percent of truck miles are driven in a less polluting manner.

2.2 DESCRIPTION OF EMISSIONS TESTING SYSTEM EQUIPMENT

Acurex Environmental has devised a unique approach to meeting the need for in-use measurement of NO_x emissions from heavy-duty vehicles. This approach is conceptually similar to, and takes advantage of, work in continuous emissions monitoring (CEM) for stationary sources such as utility boilers. The approach involves the use of a dilution sampling system, which features total preservation of the exhaust sample without condensation or other losses of sample integrity associated with conventional techniques. Gram-per-mile emissions could be continuously determined from exhaust gas concentrations and engine air flow. ARB and EPA sponsored this project (Development and Testing of On-Board Measurement Capabilities for Heavy-Duty Trucks) under contracts 92-924 and 68-D2-0063. The work performed under these contract awards was to measure vehicle NO_x emissions from a diesel truck, first while operating on a chassis dynamometer, and second, while operating over the road. The work performed is described in later sections of this report.

The sampling system described in the following sections was adapted from a stationary source emission measurement method and was used during this project to measure the air pollutants of interest from mobile emission sources. The method and apparatus permit the continuous measurement of emissions from these sources and relate the engine performance directly to pollutant emission concentrations. The apparatus is designed for use while the mobile source is stationary (operating on a chassis dynamometer) or moving in actual traffic, although optimization and further development is still required.

Tailpipe emissions from mobile sources such as cars and trucks are typically measured on a chassis dynamometer. The vehicle is mounted on the dynamometer and the tailpipe exhaust is routed to a dilution chamber for measurement. The vehicle is operated in a prescribed operating cycle designed to simulate actual operating conditions on the road. The emissions measured are related to emissions on a gram-per-mile basis by a prescribed computational algorithm. This method of measurement does not necessarily simulate all of the nuances of on-road driving and therefore gives rise to the potential for over- or under- estimation of vehicle emissions. The method presented here allows for the direct measurement of engine performance and related emissions, and permits the computation of emissions for various operating cycles.

The principal feature of the apparatus an improved emission measuring apparatus that collects engine performance data in conjunction with emission concentration measurements that are then analytically combined to yield emission performance data based on engine performance during transient and steady state operation. Parameters measured included:

Engine parameters

- Engine speed (rpm)
- Vehicle speed
- Throttle position
- Air mass flow

Emission Concentration Measurements

- Emission concentration measurements in the exhaust flow are typically made for CO_2, CO, NO_x, HC and O_2 although other parameters can be measured

Engine operating parameters were measured by installing the following types of sensors at appropriate locations on the vehicle. Engine speed (rpm) was measured with standard magnetic or optical pulse sensors commonly installed on cars or trucks on the input shaft to the transmission. Vehicle speed was measured in a similar fashion at the output shaft of the transmission. Throttle position was provided by a voltage signal generated by a position potentiometer. Air mass flow was measured by installing a flow measurement section on the intake of the engine and installing temperature and flow sensors on the air-intake manifold directly. Flow sensors typically consist of a thermocouple to measure temperature and single or multiple hot wire anemometers to measure flow velocity. Mass flow is then computed from the parameters measured and the knowledge of duct area. If flow disturbances are expected over the full flow range to be measured, calibration procedures should be incorporated to correct for any discrepancies. Hot wire anemometers were the preferred method to measure flow velocity due to their very low pressure drop on the flow stream and minimal influence on engine performance. Multiple hot-wire anemometers were used to improve the accuracy of the air flow measurement over the entire operating range of the mobile source. The accuracy of hot-wire anemometers and instruments in general is customarily specified to a percent-of-full-scale. An accuracy of 2 percent-of-full-scale would result in a measurement accuracy of plus or minus 20 percent for a measurement of 10 percent of full scale. The use of multiple hot-wire anemometers of different sensitivities and ranges could improve the measurement accuracy of the system, particularly in the low engine rpm range (< 1,000 rpm). It is likely that each different tractor would require some custom adaptation and installation of the sensors and probes, since few tractors are exactly the same. Acurex Environmental attempted to standardize the equipment as much as possible.

Flow sensor data, temperature, and the cross-sectional area of the duct are then combined to yield total air mass flow. Air flow should be proportional to the engine rpm at low load conditions when the turbocharger is not working. This check could be performed in the data acquisition and analysis portion of the system. Finally, transmission output shaft speed provides a signal that is directly proportional to vehicle speed. The relationship of transmission input rpm to output rpm provides an indication of vehicle gear setting.

An extraction-dilution emission concentration measurement system was used to make emission concentration measurements. Extraction-dilution emission concentration measurement systems have only been applied to stationary utility or process stack emission measurements up to this point. The technology is relatively new, but has developed a significant following due to its superior ability to preserve the emission sample and therefore make more accurate emission measurements than is possible with more conventional extractive-sample conditioning systems. The concept utilizes dew-point suppression by diluting the emission sample (by a fixed ratio) with clean, dry air. The extraction-dilution system is modified to provide fast response to permit the tracking of emission concentration changes due to engine transients.

Another feature of the system was the provision to combine the measured parameters with computational algorithms, and to report engine performance parameters versus emission concentration values or versus vehicle emission rates/mile for city or highway driving conditions over prescribed engine operating cycles. Figure 2-1 shows the schematic arrangement of the various sensors that were used in this project and their respective mounting locations on the vehicle.

The advantages of an extraction-dilution emission measurement system over a conventional extractive system are as follows:

Extraction-dilution systems are much less prone to system problems, since they do not use condensing sample conditioning systems. Condensing sample conditioning systems require heated sample lines to transport the sample from the sample port to the sample conditioning system. The sample conditioning system cools the sample and removes the condensate from the gas. The dry sample gas is then passed through analyzers for measurement. The extractive, condensing types of systems typically suffer from heated sample line failures, plugging, corrosion and various other problems. The extraction, condensing systems do not measure total NO_x, because NO_2 condenses in cool sample lines and in some sample conditioners. Only a portion of the NO_2 survives to reach the analyzer. The dilution probe concept eliminates all of these problems due to its unique operating principles.

The extraction-dilution emission measurement system performs in-situ sample conditioning at the probe tip by diluting the filtered sample gas with clean dry air. The dilution ratio is chosen

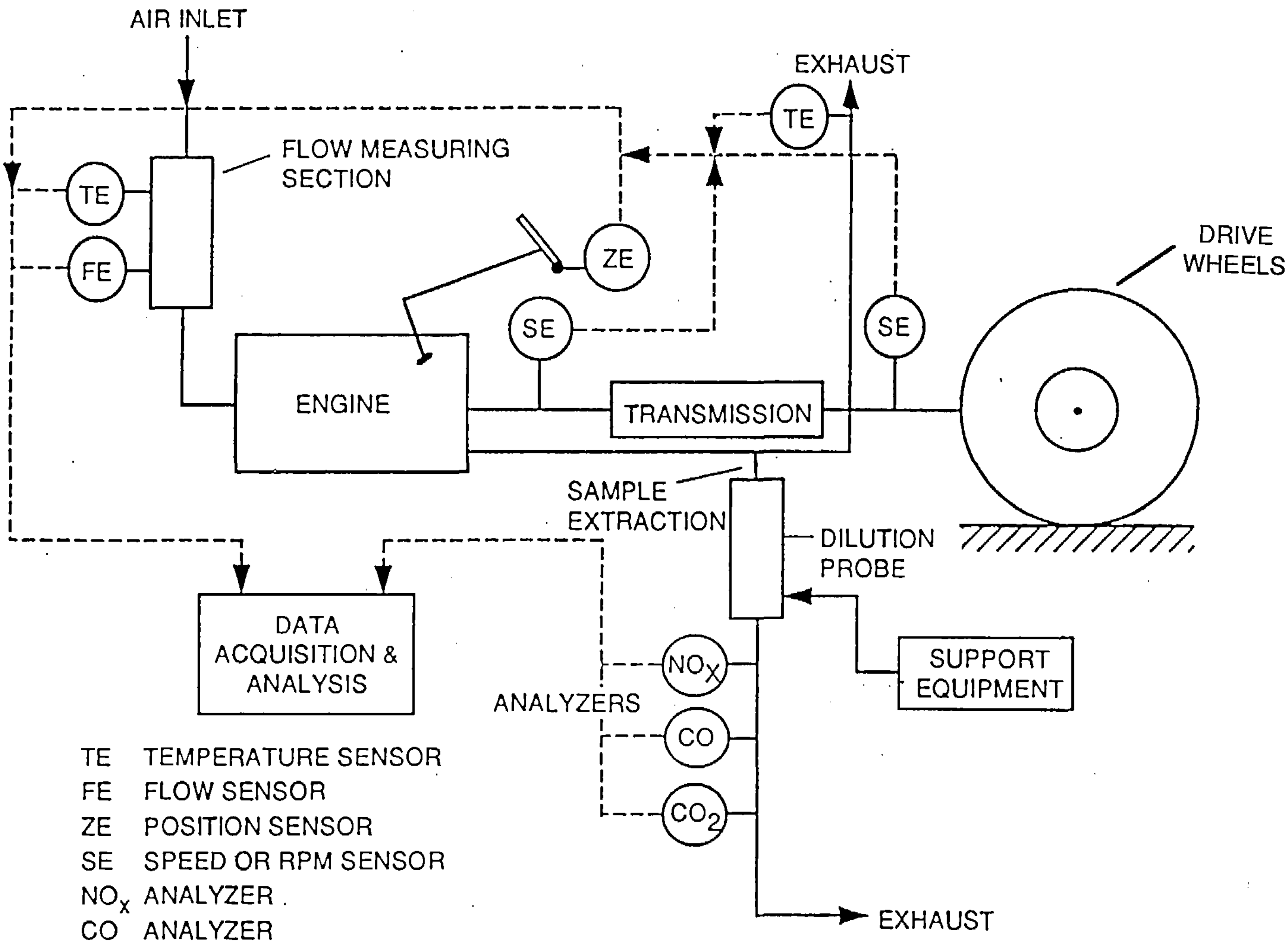

Figure 2-1. Emission sampling system

to ensure that no condensation occurs in the sample lines (under all weather conditions) while matching analyzer measurement ranges. The dilution ratio used in this analysis was 100 to 1, but this can be adjusted. The sample gas is drawn through a sonic orifice by an aspirator. The aspirator is operated by the dilution air, and the sample-gas-to-dilution air ratio is fixed by the geometry of the device. The sample gas dew-point is lowered by dilution with the dry air, eliminating the need for heated sample lines and other sample gas conditioning equipment. Aspirator operation holds the sample line under positive pressure, ensuring that sample integrity is maintained. Since moisture is not removed from the sample, measurements are made on a wet basis—the EPA preferred method. Analyzers used with these systems are EPA-approved monitors typically used for ambient air monitoring.

Since the sample is diluted by a factor of 100 or more, much lower sample gas flowrates pass through the probe filters. The effect is that these filters need to be cleaned less frequently than those of extractive types of systems. It has been demonstrated that back purging of these filters is effective, and probe maintenance has not been required for extended periods of time.

The entire continuous emissions monitoring system requires only limited external connections and is uncomplicated. Instrument air, electrical power, calibration gases, process data lines, and sample lines connect to the emissions measurement cabinet.

2.3 EXTRACTION-DILUTION SYSTEM EQUIPMENT CONFIGURATION

Process and Instrumentation

The equipment configuration for the mobile emission test system is shown in Figure 2-2. The system can be divided into several subsystems, each of which is discussed in greater detail in the following sections:

- Dilution air system
- Flow controls
- Dilution probe umbilicals
- Dilution probes
- Analyzers
- Calibration gas supply
- Controller and I/O interface system
- Operator interface, data acquisition and report generation system
- Uninterruptible power supply protection

<u>Dilution Air System</u>

The dilution air system provides clean dry air to the dilution probe. Instrument air from a small compressor was used as the supply. Depending on the condition of the air, various methods

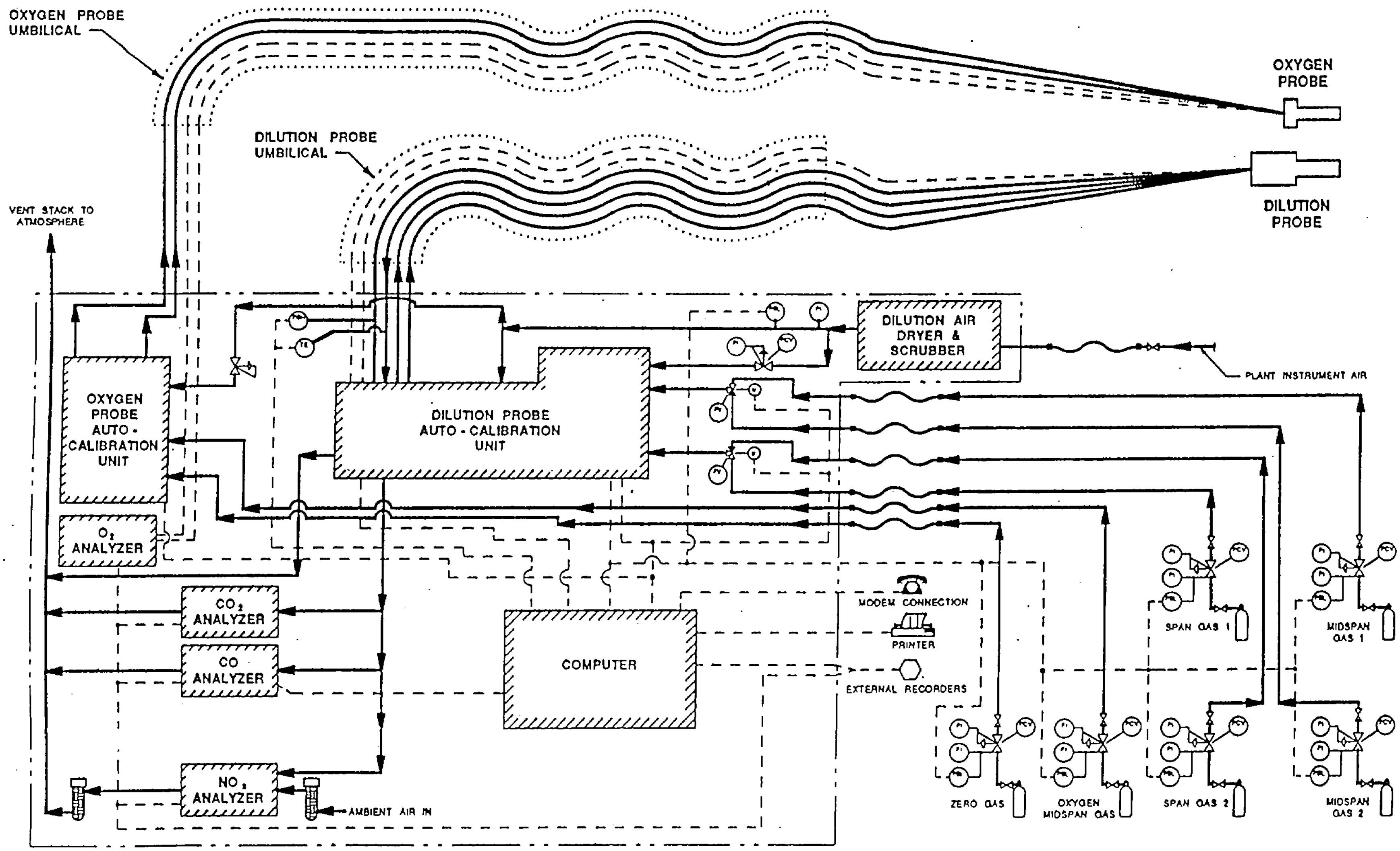

Figure 2-2. Process and instrumentation diagrams of the extractive filtration system

or systems are required to clean the air to the degree required. For example, if CO is measured, a special CO scrubber is necessary. An air pressure of 80 psig is sufficient for the system. Pre-filters remove the largest contaminants. A regenerative dryer is used to remove moisture. An accumulator provides air when the demand on the system is high, as is the case during purge flow. Final scrubbing of the air is accomplished with a Purafil and charcoal filter. Typical air flow per dilution probe is 1 scfm at 80 psig. The dilution air is also used as "zero" air for the analyzers. "Zeroing" the analyzers with the dilution air provides a background measurement so that any contaminants present in the dilution air will be subtracted from the exhaust gas concentration.

Flow Controls

The flow control system of the dilution system is uncomplicated, with three main air flow circuits: the dilution air flow, purge air flow, and the "zero" calibration air flow. Flow control is achieved with pressure regulation and critical orifices. The pressure for the dilution air is approximately 40 psig.

The second air circuit provides purge air to clean the filter at the tip of the probe. The pressure setting for this circuit is exhaust-contamination-dependent and the pressure setting can vary from 15 to 40 psig. Purge flow varies between 8 to 14 scfh.

The third air circuit is dedicated to "zero" air flow. When the dilution probe is calibrated, "zero" air gas or calibration gas passes through a critical orifice establishing a pre-determined flowrate for calibration. The flowrate has to be sufficiently high to fill the front of the dilution probe with calibration gas. Excess gas will spill out of the front of the probe, preventing exhaust gases from entering the probe during this procedure. The entire system train is thus checked and calibrated. Flow velocity through the umbilical was typically 10 ft/sec in a 1/4-inch diameter tube. Calibration gases reach the analyzers in 5 seconds for umbilicals approximately 50 ft long.

Dilution Probe Umbilicals

The dilution probe umbilicals for the system consist of continuous tubing encased in a polyethylene jacket. The sample, air and vacuum lines are Teflon.

Dilution Probe

Figure 2-3 shows the internals of the adapted dilution probe. All probe parts exposed to the exhaust gases are constructed of Inconel, Hastelloy, stainless steel, and Pyrex glass. The materials were carefully selected to prevent corrosion due to the exhaust gases. Standard probes in stationary-source use typically operate at temperatures as high as 750°F to 1,100°F.

The probe consists of a probe sheath that is inserted into the exhaust stream through a port. The end of the probe is open, allowing sample gas to enter the probe body through a coarse filter. Typical installations extract exhaust gas at a rate of 1 to 3 in^3/min, which is equivalent to extracting one cubic yard of exhaust gas in 11 to 33 days. This 10 W sampling rate minimizes the maintenance required on the probe. The diluted sample gas is transported directly to the analyzers at a rate of approximately 10 ft/sec. The sample gas enters a quartz sonic orifice through a fine quartz wool filter. Exhaust gas is drawn through the orifice by the vacuum created via aspiration by the dilution air primary nozzle. To ensure proper operation, the aspirator is monitored by observing the vacuum. A gauge in the analyzer cabinet indicates the probe vacuum and a pressure switch provides an alarm, should the vacuum drop below acceptable levels. When the system is calibrated, calibration gas is introduced into the front chamber of the probe and the chamber is flooded with calibration gas.

The probe cavity is evacuated during normal operation by the sonic sampling orifice and a by-pass pump drawing exhaust gas through the calibration gas port. The by-pass flow significantly improves the response time of the sampling system and permits more accurate correlation of emission concentration measurements with engine operating performance.

Analyzers

The analyzers selected for this system are typical non-dispersive infrared (NDIR), for CO and CO_2 measurement, and Chemiluminescence Detectors for NO_x. At a dilution ratio of 100:1, an analyzer range of 0 to 10 ppm would be required for the expected 1000 ppm NO_x maximum emission level. Because many ranges are available, dilution ratios could be tailored for a particular

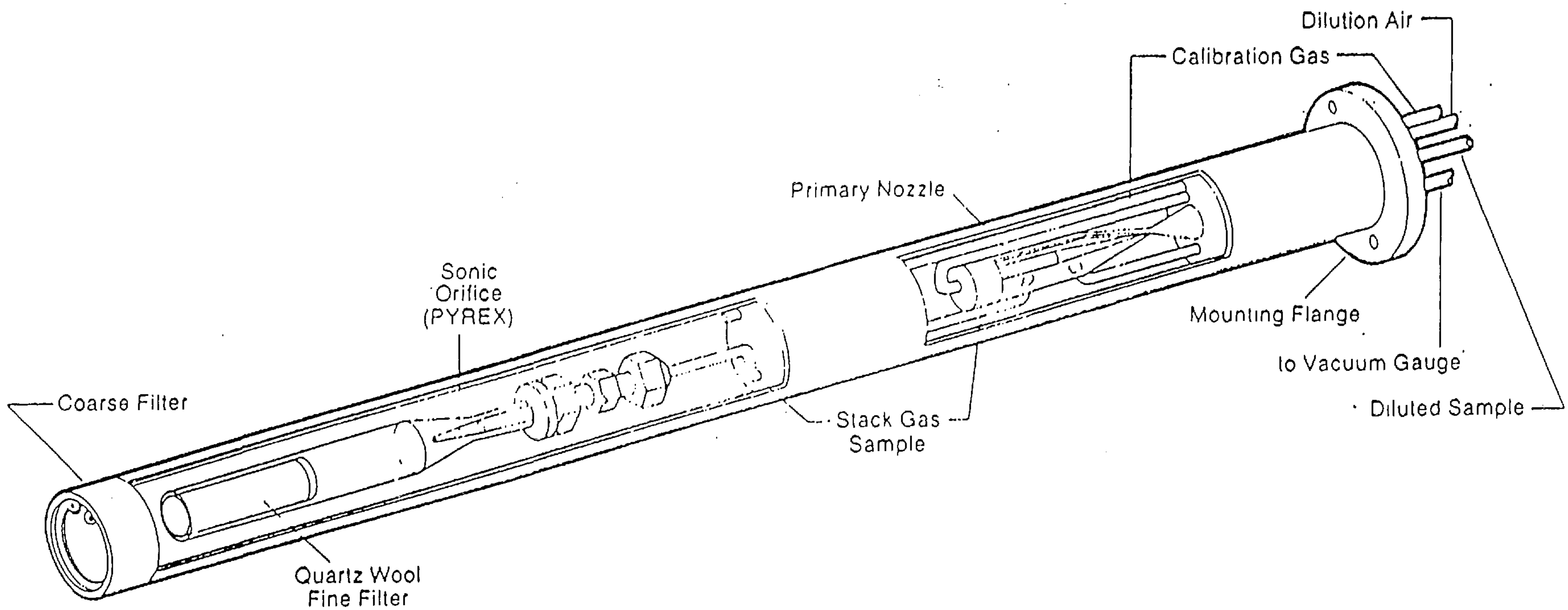

Figure 2-3. Dilution probe

application as needed. Response time is also selectable. For this project, selecting the lowest dilution ratio possible was optimum because the response time of the analyzers increases with decreasing emission concentrations.

Controller and I/O Interface System

The entire continuous emission monitoring system is controlled by an industrial grade controller and I/O hardware. The system requires design flexibility to accommodate added data acquisition channels to record operating data of the engine and perform computations.

The controller and I/O interface system in the DILU-CEM 500 utilize a "Mistic 100" controller and Opto 22 I/O hardware. While configurations can also satisfy control and interface requirements, the Opto packaging concept was selected for the Acurex system because it provides extraordinary ease of expansion and modification. The controller has wide ranging capabilities far beyond ladder logic and represents the latest in reliable control technology. This technology was attractive because of expansion capability without wiring. The available I/O modules address all known I/O types—analog, pulse, discrete, ASCII, etc.

Operator Interface, Data Acquisition and Report Generation System

The operator interface, data acquisition and report generation system is mounted in the analyzer cabinet. The system consists of an IBM-compatible personal computer with sufficient memory, storage capacity, monitor, and printer. The operator interface communicates with the controller, downloads control routines as needed, and receives data from the I/O channels via RS-422 multidrop communications line. The operator interface can be located away from the analyzer cabinet, and, in the future, remote communications could be established via cellular link.

The operator interface uses process monitoring and a control software package with extensive capabilities. It provides for all capabilities, necessary controls, computations, communication links, data acquisition, report generation, and local and remote operator interfaces.

Uninterruptible Power Supply Power Protection

The extractive-dilution system incorporates an uninterruptible power supply (UPS) because the operator interface station, controller and I/O must be protected from power surges, brownouts and power interruptions for at least short durations of 5 to 10 minutes to prevent analyzers from going off line in the event of very short interruptions. Analyzers require significant time to stabilize once they have been turned off and this could lead to unacceptably large data outages. The system was supplied with a UPS to protect the system for up to 10 minutes.

System Setup

The self-contained dilution sampling system was mounted in a trailer. The emission measurement trailer was loaded onto a low-boy trailer only to discover that the Superbus tractor had a lower than standard hitch height. Fortunately, a medium height trailer was located that was functional, although it required the removal of the wheels from the emissions measurement trailer. Figures 2-4 and 2-5 show the loading of the emission measurement trailer onto the truck trailer. The tractor was first tested in the LACMTA chassis dynamometer. The trailer-mounted emission system was later loaded onto a low-boy flat-bed trailer for on-road testing. Probes and instruments were mounted on the tractor and umbilicals routed to the trailer to measure emission levels and to record the data. The dilution system owned by Acurex Environmental was designed for utility use. Size and weight was not of primary consideration during these tests to demonstrate the concept. For extended use in mobile applications, the equipment size and weight could be substantially reduced with design optimization.

Advantages of the Apparatus

The advantages of dilution probe continuous emission system are numerous. Ambient air monitors, which have been in use for very long periods, have been certified by the EPA and are being used in these systems. The sensitivity of the analyzers has been shown to be high and sufficient even at very high dilution ratios and low concentrations.

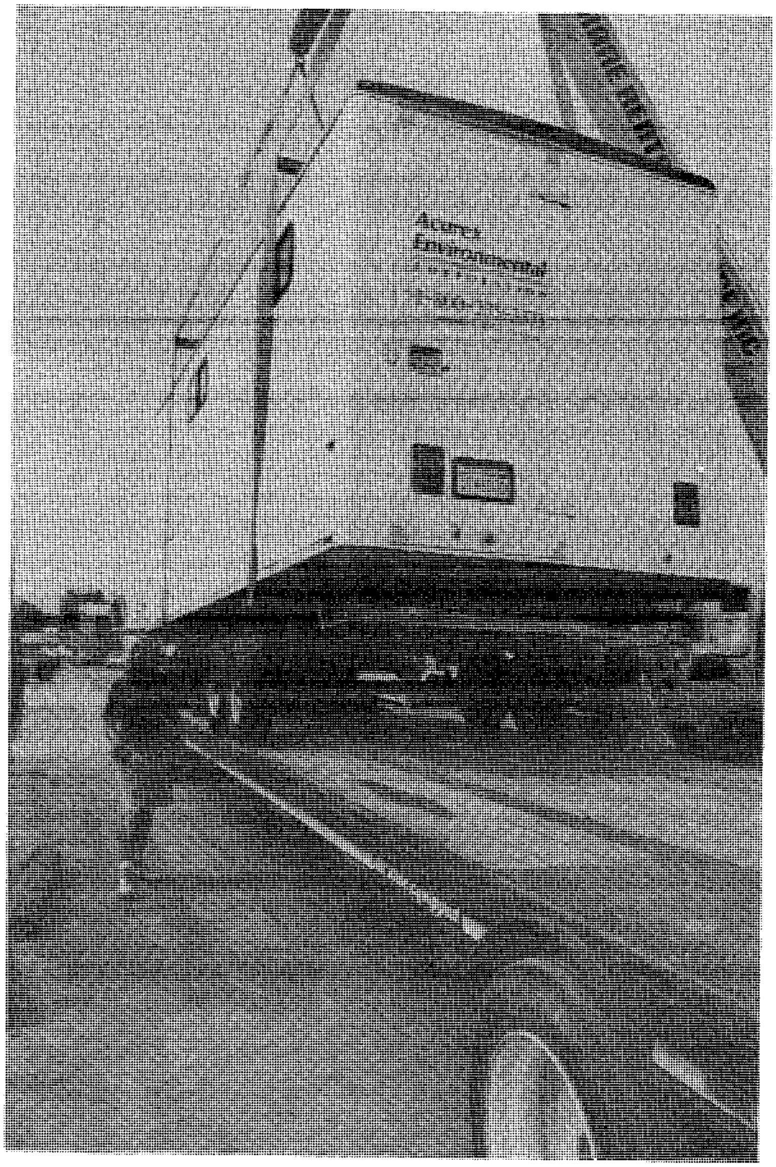

Figure 2-4. Loading of trailer

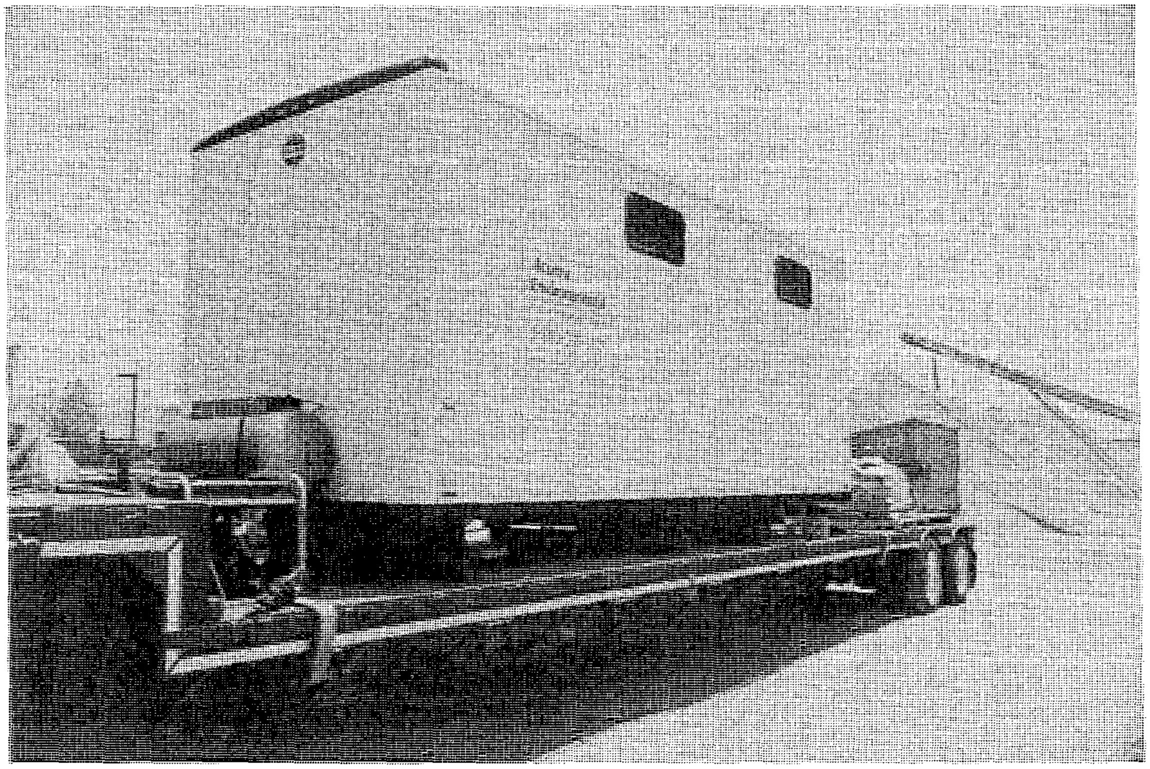

Figure 2-5. Equipment arrangement on the trailer

The advantages offered by the apparatus are as follows:

- Dilution systems do not require heated sample lines to maintain sample integrity, resulting in major cost and maintenance reductions. The opportunity to operate without heated sample lines also results in reduced power consumption.
- Extraction-dilution systems have been demonstrated to operate maintenance free for long periods of time. Instrument calibration and servicing of calibration gas bottles is required approximately once per month.
- The simple design and extreme test flexibility make this type of system the system of choice. Analyzers for other species of gases can be added if needed, although they will require additional calibration gas bottles and procedures.

- The I/O system provides for large I/O expansion capability and flexibility without major redesign. I/O modules are of simple plug-in or add-on configuration without the need for wiring.
- The process control and monitoring software has extensive computational capability that can easily handle all required control, data acquisition, analysis, and reporting tasks.
- The operator interface is equipped with a large data storage and handling capability which allows for remote downloading of data if needed.

SECTION 3

SAMPLING SYSTEM ADAPTATIONS FOR MOBILE SERVICE

3.1 INTRODUCTION

The dilution sampling system described in the prior section was previously used in a utility continuous emissions monitoring environment and was not originally designed for mobile service. Although the equipment was already shock-absorber-mounted in its trailer for unpowered towing, it was not equipped for operation while moving. Some components of the original system were so large and fragile that they were not suited to be mounted on a vehicle in a dynamic environment which would expose them to significant mechanical shock during operation. A number of system modifications were necessary to address these issues, particularly with regard to power supply. The sensitive analyzers require relatively "clean" power to provide accurate results. As will be discussed in Section 5, some of the requirements were underestimated and this resulted in numerous problems causing significant test delays and increased costs.

The project proceeded in two phases. Phase I was the testing of a vehicle in the LACMTA chassis dynamometer, and Phase II was the on-road testing.

The test vehicle was an Orange County Transit Authority Superbus (Unit #7001) with a 58-passenger capacity (Figure 3-1[1]). This tractor was selected because it had a single exhaust stack (see Figure 3-2) which would make the adaptation of instrumentation easier than with dual stack configurations. The empty weight of the bus was 35,900 lbs., with a capacity limit of 55,000 lbs. The

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[1] As shown in Figure 3-1, the Superbus is actually a tractor-trailer configuration with the trailer providing passenger seating and the tractor serving as the segregated power source to move the trailer. This vehicle was selected in past because the tractor was not in daily use and its owner was able to make it available for the extended period needed for this program.

Figure 3-1. OCTA Superbus #7001. The Superbus is a tractor-trailer configuration with the trailer providing passenger seating and the tractor servicing as the segregated power source to move the trailer

Figure 3-2. The Superbus has a single stack configuration, ideal for adapting the instrumentation

bus was powered by a 1991 Cummins L10-280 hp engine (Serial #S 34682105) and was equipped with an Allison HT 748 (ATEC) electronic transmission.

The emissions sampling system trailer and the sampling cabinets inside the trailer are shown in Figure 3-3 and 3-4. Several modifications to the emissions sampling system were performed which made the equipment suitable for testing in the chassis dynamometer facility as well as on-road. These modifications were as follows:

- Adapt the large dilution-extraction utility stack probe to a mobile environment
- Improve the response time of the sampling system by reducing the length of sample lines, and allowing quick volumetric sample turnover in the sampling cavity of the probe
- Modify inlet air duct to measure air flow
- Exchange the PC hard drives with more shock resistant Bernoulli removable cartridge disk drives

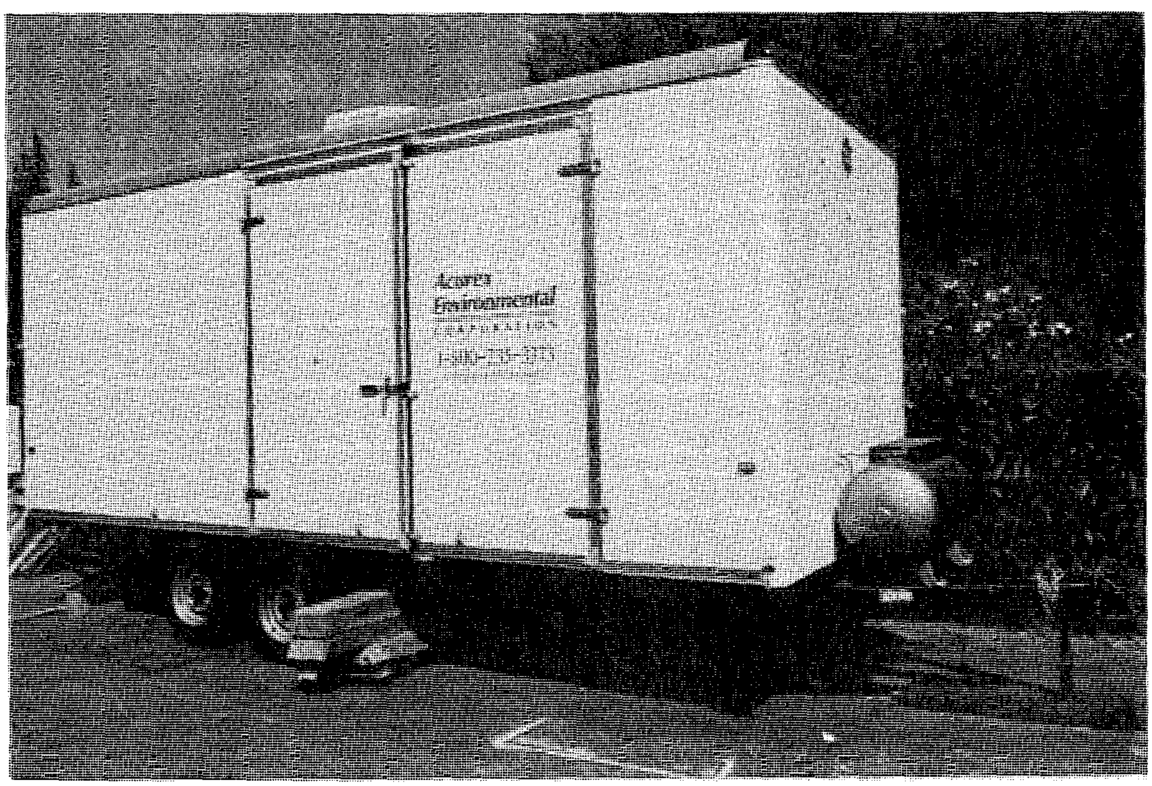


Figure 3-3. The Acurex Environmental emissions sampling system trailer

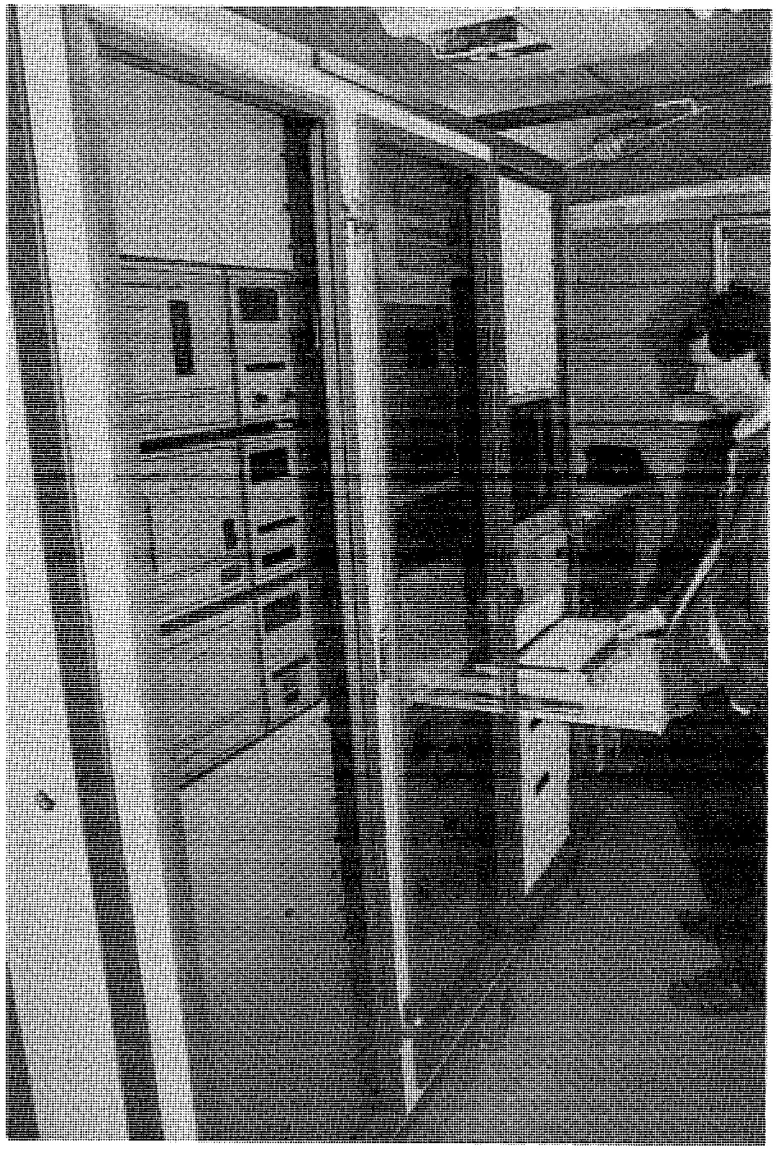


Figure 3-4. Emissions sampling system cabinets with PC operator interface

- Modify the software program in the emissions sampling system to record the selected engine parameters and emission concentration levels. Develop computational algorithms to determine emissions on a gram-per-mile basis
- Determine the connection points for auxiliary sensors or install new sensors on the vehicle
- Specify portable power needs and procure suitable equipment for on-road testing

- Evaluate the feasibility of equipment configurations and load variations during on-road testing

3.2 EMISSIONS SAMPLING SYSTEM AND BUS MODIFICATIONS

3.2.1 Dilution Probe Adaptation

The standard dilution probe utilized in utility stacks consists of stainless steel structural tubing and the heart of the dilution system, the extractive dilution aspirator, which is contained in a much smaller stainless steel housing. In utility applications, response time is usually relatively unimportant, and response times on the order of several minutes are acceptable. Samples are usually recorded once every 15 minutes based on 1-minute averages. For mobile emissions monitoring, because of the need to relate short-term emissions variations with vehicle operating parameters, slow response times are unacceptable. The dilution probe needed to have a very small sample volume for quick response and the sampling cavity volume in the probe itself needed to be minimized, because the probe's sample intake volume is very small. The dilution aspirator's large housing was removed, and a smaller housing was designed and attached directly to the truck stack. It was economical to simply modify a new exhaust stack with the appropriate fittings. The design is shown in Figure 3-5.

3.2.2 Response Time Optimization

The original dilution probe aspirator cavity was several cubic inches in volume, and several minutes would elapse before new exhaust gas from the exhaust duct would enter the sampling probe. This volume had to be reduced to improve the response time of the system. The aspirator itself is made from quartz or pyrex and has a very irregular shape that lends itself poorly to enclosure in a smaller cavity. Acurex Environmental therefore decided to fill the cavity with stainless steel balls to reduce the gaseous volume of the cavity. In addition, a sampling pump was attached to the calibration gas port that would continuously pull exhaust gas through the aspirator

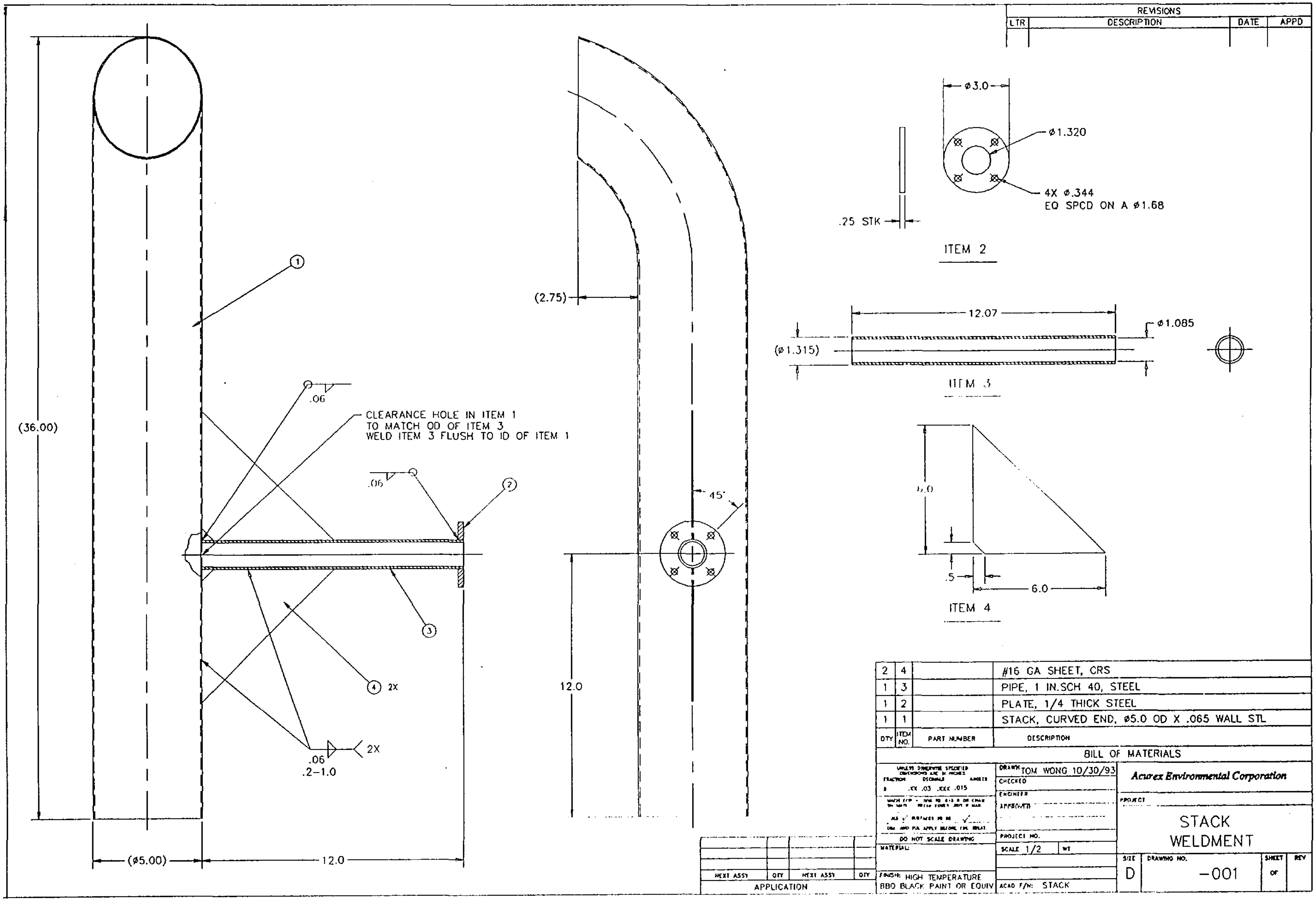


Figure 3-5. Superbus tractor exhaust stack weldment

cavity and cause quick exchanges of the gas within this volume. Response time of this part of the system was thereby improved from several minutes to a few seconds.

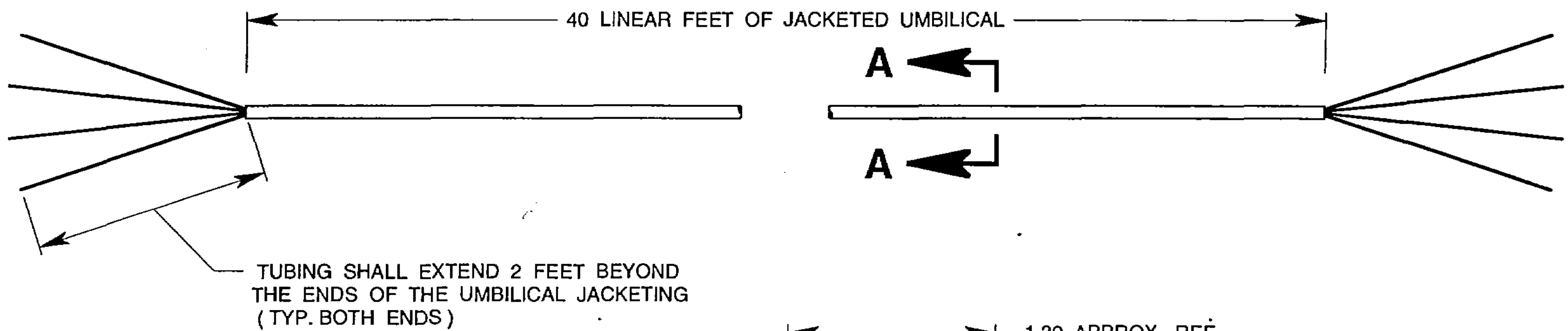
Response time of the system through the umbilical sampling hose is directly proportional to its length and was calculated to be 1 sec./10 ft. A new umbilical of 40-ft length was specified (Figure 3-6).

Analyzer response time is variable and depends on the analyzer cavity. It can only be improved via the sampling rate through the analyzer. Stable readings through the analyzer are usually averaged and little can be done to improve the response time further. Inquiries with the various manufacturers also suggest that lower concentrations require longer time constants for the instruments. Therefore, diluting the sample lengthens the response time. Test data was evaluated to show what emission changes were noted in response to sudden load changes and noting the time lag before the readings on emissions stabilized.

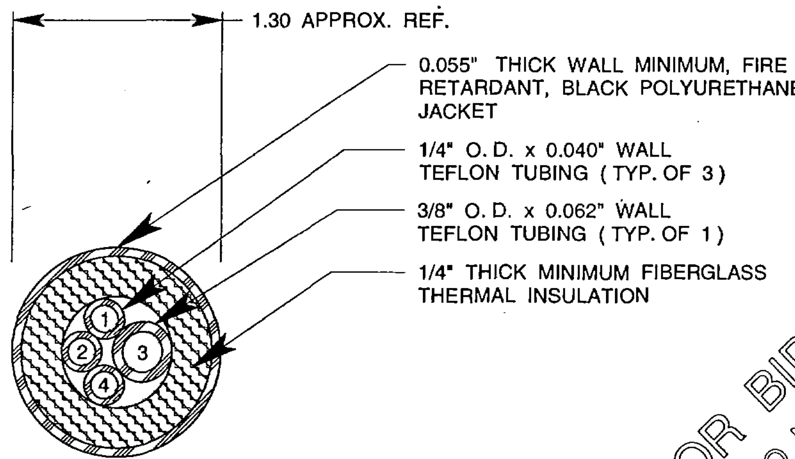
3.2.3 Inlet Air Duct Modifications and Instrumentation

Concern over the influence of typical flow elements such as orifices on engine performance dictated the use of anemometers in the inlet duct without restricting the air flow. A redesigned duct, shown in Figure 3-7, provided for the mounting of two anemometers and a thermocouple. The anemometers were mounted with their sensing heads at the center of the tube and at 1/2 the radius to discern the velocity profile in the duct. Additionally, strain relief tabs were provided to support the instrumentation heads with spanners. The installed instrumentation is shown in Figures 3-8 and 3-9. The dilution aspiration probe is shown inserted into the side of the exhaust stack of the truck on the left and the anemometers are shown on the inlet air duct on the right. The large instrumentation housings holding the transmitters are supported by the spanners.

The inlet air test section was tested to confirm the flow sensitivity of the sensors. The calibration chart is shown in Figure 3-10. This test showed that the inlet air flow section performed well when the flow was not stratified. In the actual installation on the tractor the air flow is not uniform at low flow conditions; this caused significant unanticipated measurement inaccuracies.



TUBE No.	CONTENTS	TEMPERATURE °F	PRESSURE
1	INSTRUMENT AIR	AMBIENT	80 - 100 psig
2	AIR / STACK GAS	AMBIENT	15 -24 in. Hg Vacuum
3	DILUTED STACK GAS	AMBIENT - 150	35 - 50 psig
4	CALIBRATION GAS	AMBIENT	10 - 100 psig



SECTION A - A

NOTES:

1. AMBIENT TEMPERATURE RANGE = -20 °F TO +110 °F.
2. TECHNICAL HEATERS MODEL No. MT-66T-40'.
3. UMBILICAL IS FOR PORTABLE USE. 1/4" AND 3/8" O.D. TUBING SHALL BE APPROPRIATELY REINFORCED.

Figure 3-6. Umbilical sampling line

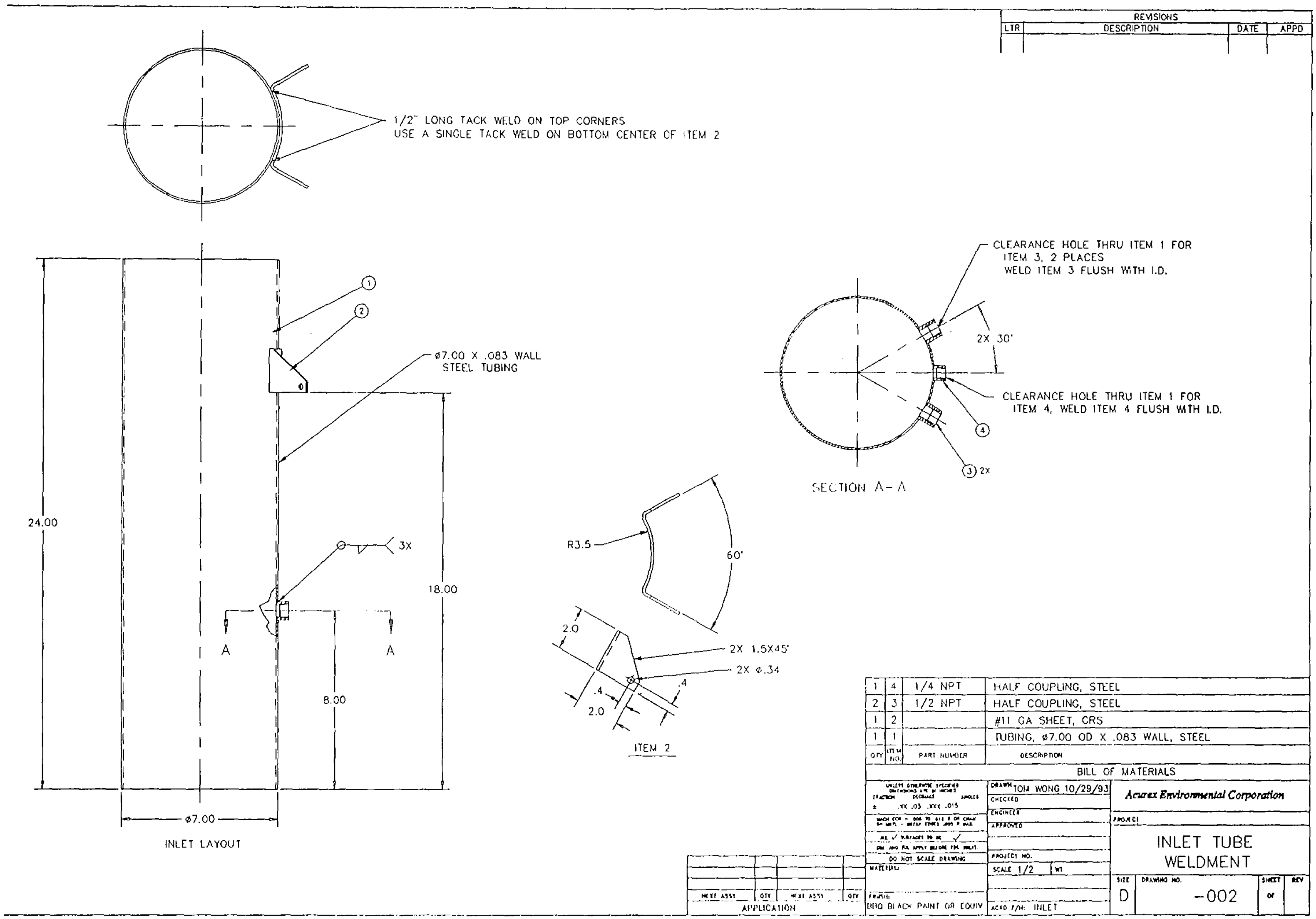


Figure 3-7. Air inlet tube weldment

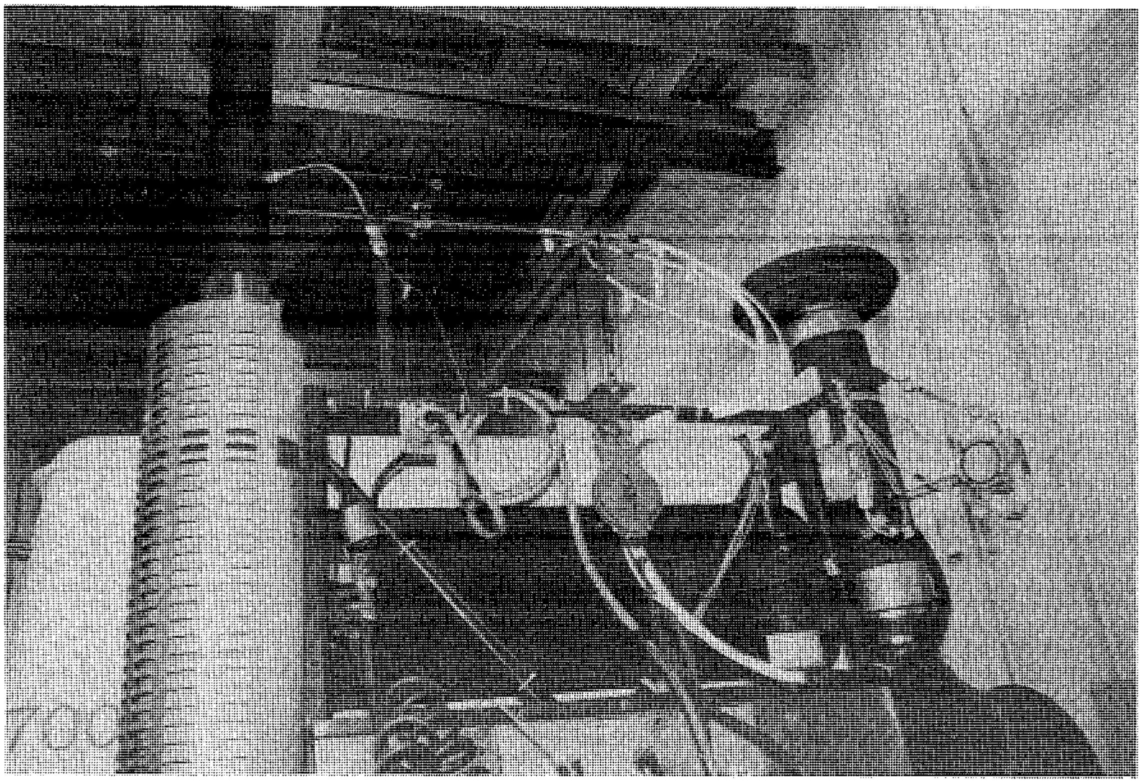


Figure 3-8. Inlet and stack instrumentation

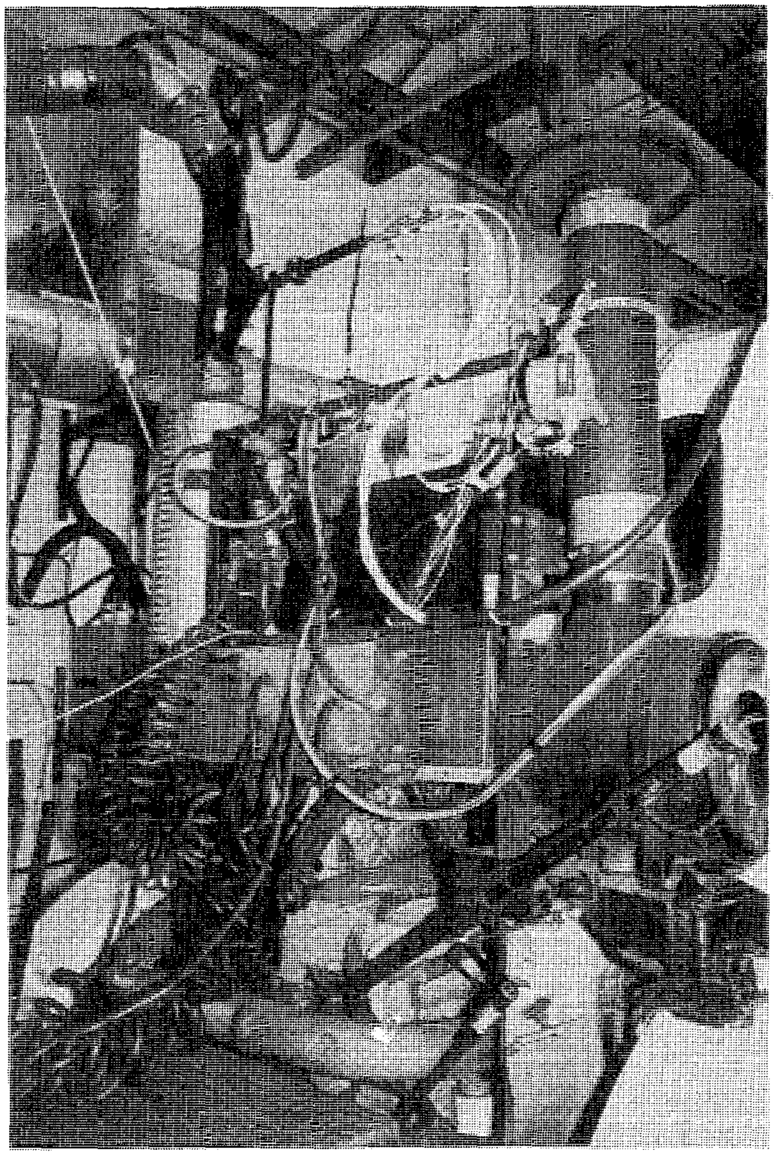


Figure 3-9. Inlet and stack instrumentation

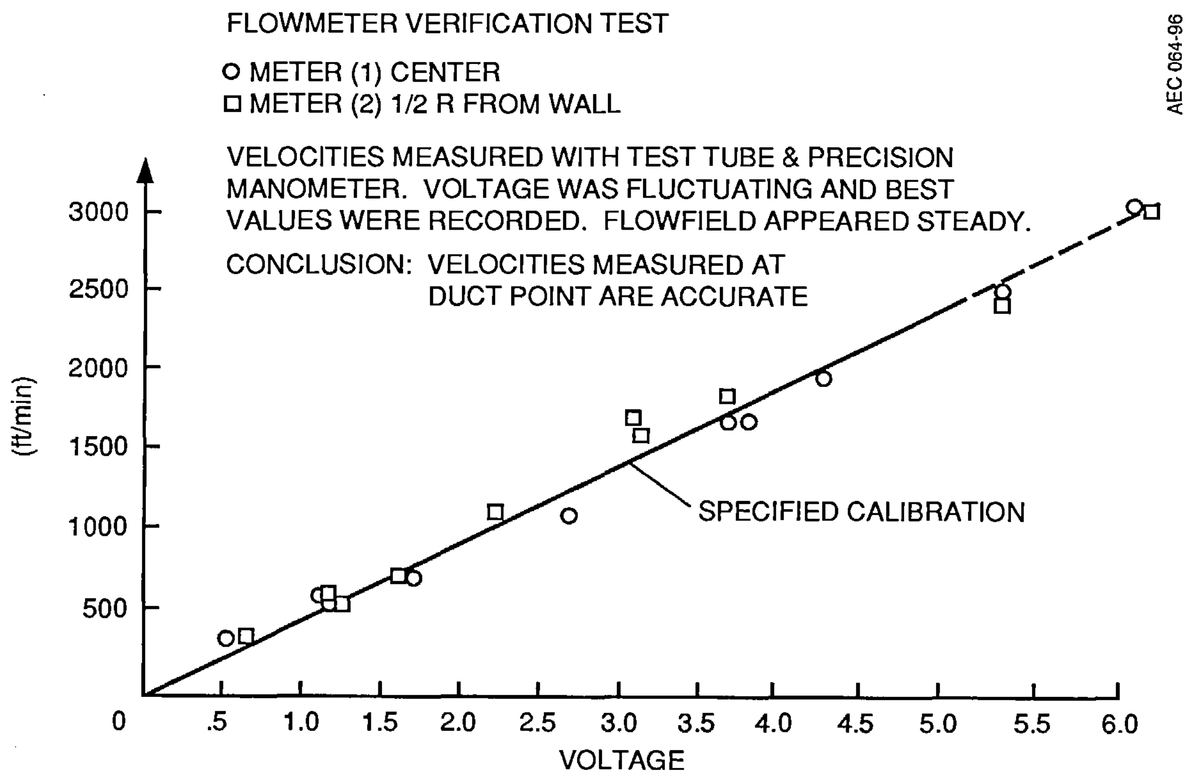


Figure 3-10. Inlet air flow measurement test

This points toward a need in future truck installations for other measurement approaches to accurately measure air flow.

3.2.4 PC Hard Drive Modifications

The hard drive in the PC operator interface and data collection computer was exchanged with a removable Bernoulli cartridge drive. Bernoulli cartridge drives are particularly resistant to shock during operation and it was judged prudent to enhance the shock resistance of the data acquisition system. The cartridge approach also permitted the quick exchange of data with other computers and permitted quick exchange of disk capacity as testing proceeded. Booting and system software was contained on the cartridges.

3.2.5 System Software Modifications

The system software of the emissions sampling system was written to test utility power stacks, and needed to be adapted to record the new parameters of interest and correct the results for the appropriate engineering units. Sampling frequency also had to be adjusted for each sensor in addition to matching the sensor input type to the appropriate I/O channel. The results of the work are reflected in Figure 3-11, which shows the new screen on the operator interface computer of the emissions sampling system. The picture was taken while the bus was not in operation.

A computational algorithm was also developed to relate the measured emission concentrations to grams-per-mile. This program was not actually loaded into the PC interface station until it had been established that the computer could handle all tasks assigned in a timely fashion. Experience with the actual data later confirmed that this was a wise choice, because data inconsistencies would not have yielded accurate results. Screening of the data became essential to yield valid results.

3.2.6 Instrumentation Connections and Quick Connector

Figure 3-12 shows the method developed to connect engine data to the emission sampling system. The tractor could be connected to the emissions sampling system in a very short time. All electronic signals from the tractor were routed to this connector. The sampling umbilical required separate tubing connectors which were routed directly to the analyzers in the emission sampling cabinet for analysis.

The possibility of connecting directly into the tractor engine control computer to download vital data was evaluated and discarded due to its costs and the liability associated with potential on-road problems. In future applications this opportunity should not be overlooked as a means of acquiring information about all operations of the engine, transmission and other vital operating parameters. Some engines are equipped with inlet air sensors that are used in the fuel/air control mechanism. However, these sensors may only provide a gross measure of air flow, not accurate

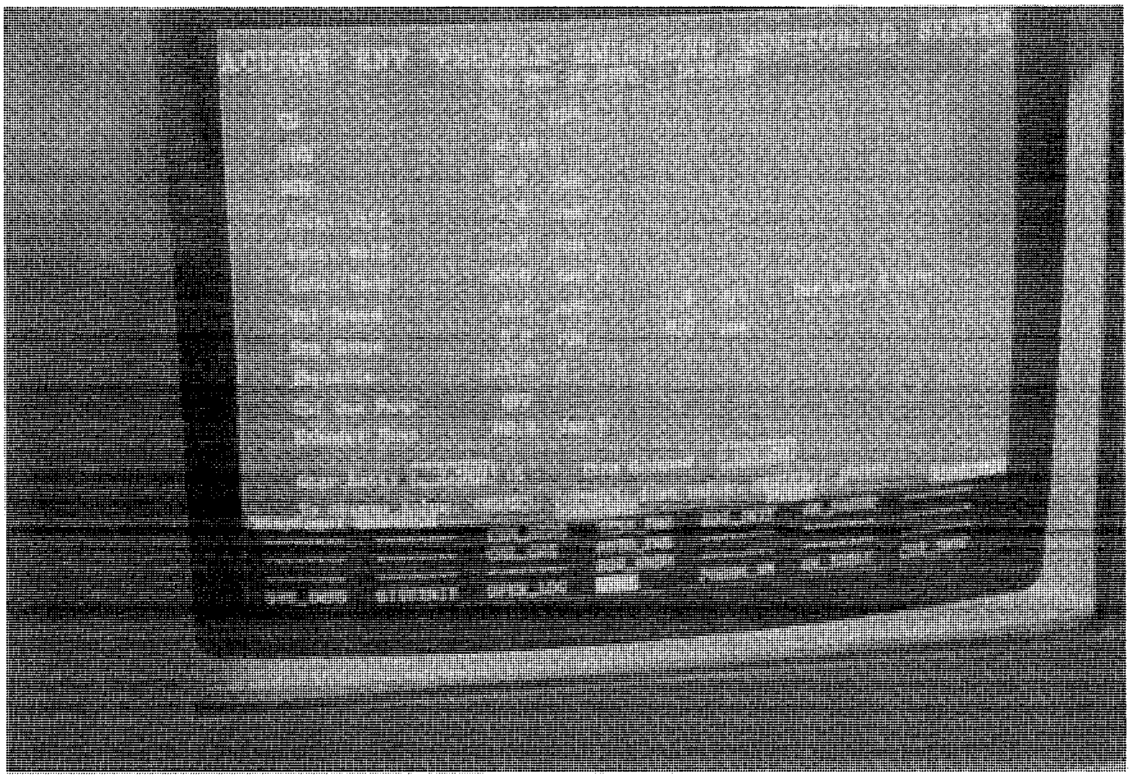


Figure 3-11. Operator interface screen on the instrument cabinet

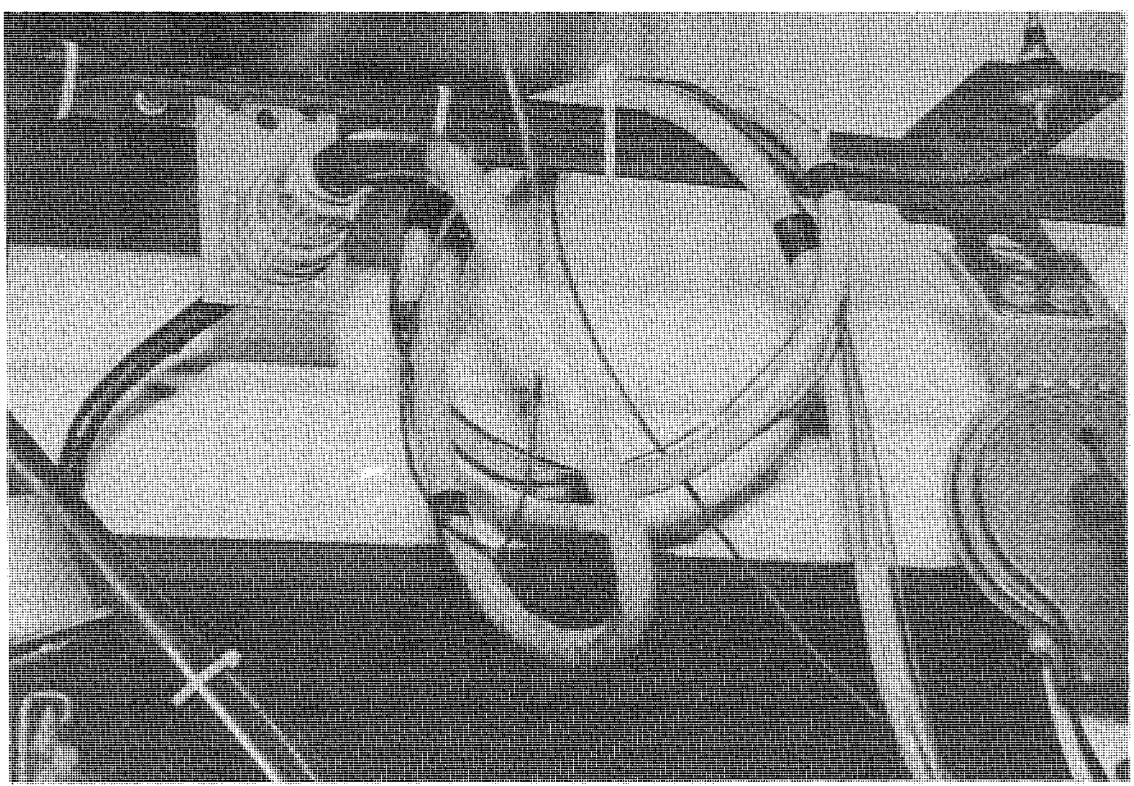


Figure 3-12. Connectors to the emissions sampling system

enough for determining second-by-second exhaust gas emissions. In addition, the control program is proprietary which would make accessing this data both time consuming and costly.

During this project other methods to obtain critical engine operating data were used by connecting to existing sensors or tapping into non-sensitive signal lines. This approach proved to be successful, although larger scale testing of trucks or buses on-road can become more cost-effective with very simplified installation of sensors or direct access to data that is readily available within the engine/transmission control system.

3.2.7 Portable and "Clean" Power for the Emission Sampling System During On-Road Testing

The large, utility-type continuous emission measurement system was not designed to be operated in a portable mode and was also not optimized for power consumption. State-of-the-art portable computers would significantly reduce the power requirements for the data acquisition and control system, and equal power savings could be realized for analyzers, air cleaning and compression systems, and the air conditioning system needed to keep the instrumentation cool.

The approach to supply power to the system was to divide the power into "dirty" and "clean" power requirements and procure separate portable power generators for each service. For this service two 4,000 W portable generators were procured that under normal circumstances would appear to satisfy the need for all equipment in the trailer. The "clean" power was furthermore passed through the uninterruptable power supply (UPS) for conditioning. This selection of equipment proved to be very troublesome during the tests and caused significant delays in collecting on-road data.

After significant effort was expended to balance the loads between all circuits to allow the units to operate continuously. A third generator was added and the circuit supplying the on-board compressor was disconnected. A separate engine driven compressor provided the necessary dilution air before this part of the system was functional.

The UPS also proved to be very troublesome. While it might be expected that a UPS would supply clean power to the load. Most UPS systems require a very steady frequency ± 2 Hz to function properly. A generator that varies in speed renders the UPS non-functional and will cause it to switch to the battery supply. The battery is, of course, quickly exhausted. The final solution to this problem was to rent a power conditioner that would rectify the incoming power 100 percent and subsequently invert the power to the frequency set on the unit.

3.2.8 Equipment Configuration for Bus Load Variations

The on-road testing was to simulate various loads during the tests to determine the influence of load variations on the performance of the bus and relate the emissions to these load variations. Plans were made to evaluate the feasibility of loading sand-bags on the trailer to be used with the bus-tractor.

Equipment configuration sketches showed that there was ample room on a low-boy trailer for the emission sampling system, power generation equipment and sufficient room to place sand bags and/or containers with "dummy" loads. The method of this approach proved correct and no difficulties were encountered during the tests.

SECTION 4

TEST PLANS

4.1 CHASSIS DYNAMOMETER TEST PLAN

Based on acceptable vehicle weights for the test vehicle, a test matrix was developed to compare the chassis dynamometer tests results with those measured by the extraction dilution system. Both systems would operate simultaneously and data would be time-stamped to make it possible to compare the results of both measuring techniques. The test plan is shown in Appendix B. Test data are provided in Appendix B, and in electronic format.

Coast-down data for the vehicle was estimated for the tests. A sequence of tests at different vehicle weight was planned to simulate what could be expected to occur in service.

4.2 ON-ROAD TEST PLAN

The on-road test plan was developed from the chassis dynamometer test plan to provide a basis for comparison. An area was located where certain special tests could be performed, such as coast down and steady-state tests. In addition, a normal bus route was selected to obtain data for an actual route which this vehicle might travel during normal service. The on-board test plan and procedures are attached in Appendix C. Because the amount of data collected during the on-road tests is so large, the data is provided in electronic format rather than hard copy.

SECTION 5

TESTING

5.1 TESTING ON THE CHASSIS DYNAMOMETER

Testing on the chassis dynamometer began in December 1993. The on-board emission measurement system was towed to the LACMTA facility. At the LACMTA site, the system was checked and calibration gases purchased for testing and all special parts for the trailer conversion were supplied. The custom parts that had been fabricated for the tractor were attached to the inlet and exhaust ducting of the tractor, and the instrumentation was wired and connected to the emission sampling system. The sensors were checked and were found to be functional. A question remained as to whether the sensor measurement ranges were sufficient for the signals to measure the parameters of interest. It was later found that the signal exceeded the range of the velocity sensors on the air intake. A suitable method was found to convert the signals from a milli-amp signal to a voltage signal which solved the problem and allowed for a 20 percent higher measurement range with good linearity. Figures 5-1 and 5-2 show the test arrangement within the test cell.

A second problem which occurred was the periodic loss of communications between the PC data acquisition system and the system controller. This caused occasional data losses of 5 to 10 seconds while the PC restored the data link. It was believed that this was due to interference problems with the electromagnetic fields in the test cell. The problem had not been observed prior to moving the system into the test cell. The problem seemed to disappear with better power conditioning, but was never entirely resolved during the active days of testing. It was speculated

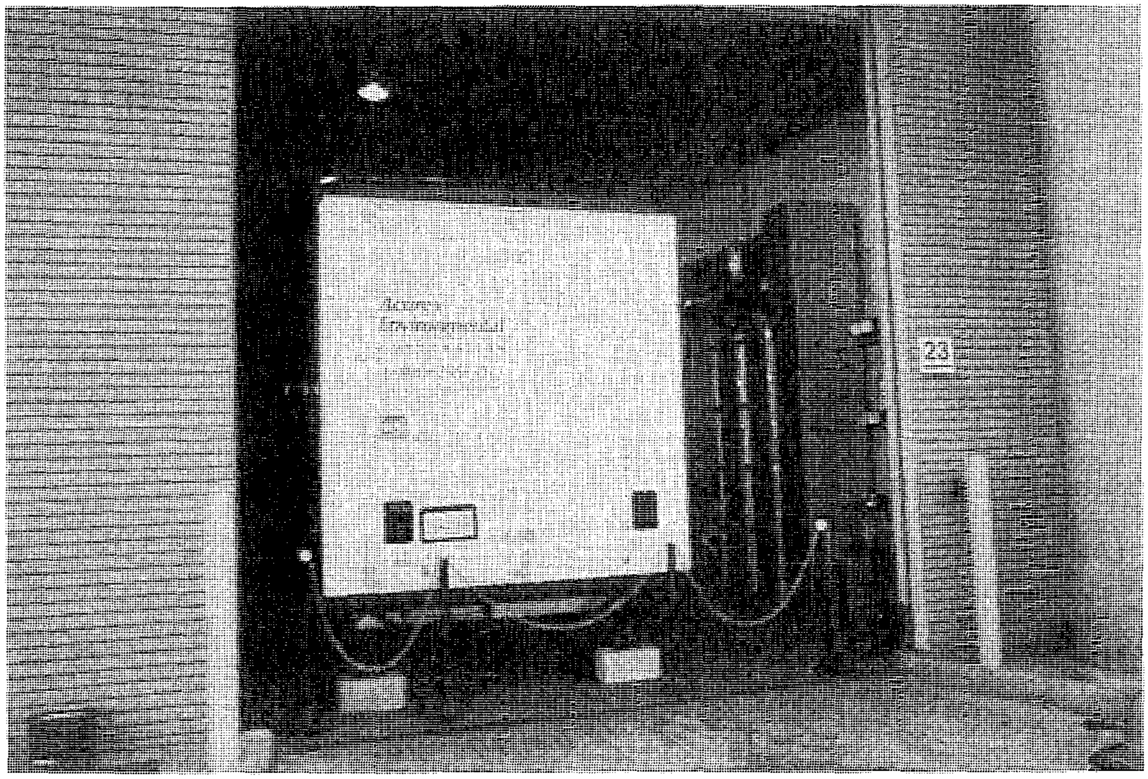


Figure 5-1. Chassis dynamometer test setup at the LACMTA facility

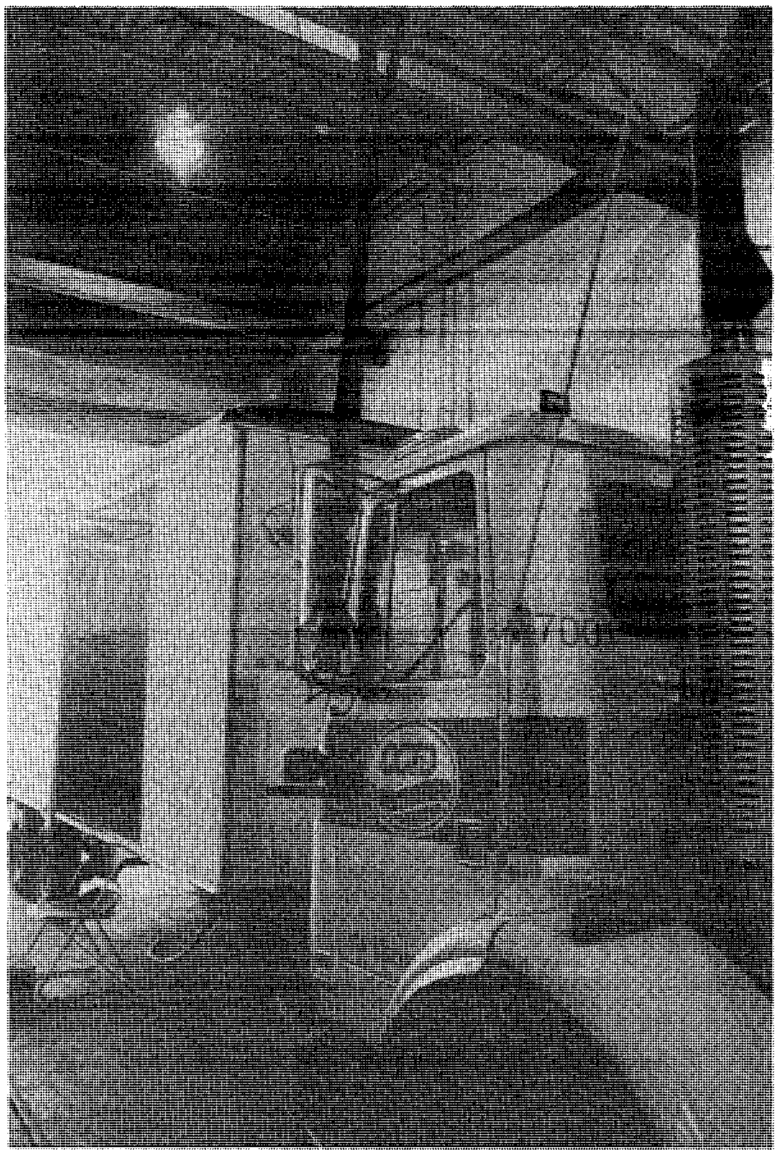


Figure 5-2. Chassis dynamometer test setup at the LACMTA facility

that the missing data for the short periods of time could be interpolated with estimates based on other similar operating conditions.

Attempts to compare the results of the chassis dynamometer measurements were unsuccessful at this time due in part to the different formats of data recording. Significant data analysis were later required to show that the measurements were indeed comparable. Comparison of some steady-state data suggested that this was, in fact, the case. The format of the chassis dynamometer test data was to be supplied in 1 second intervals rather than in summary reports which are normally generated. Summary reports provide little insight into the actual second by second measurements.

During the course of further testing it became evident that the LACMTA monitoring system was not functioning properly. An attempt was made to re-boot the system to solve a perceived software fault. Re-booting caused all prior test data to be lost. Examination of the facility later showed that a filter bag had broken and was lodged in one of the flow elements, rendering suspect all test data gathered to that point.

Acurex Environmental studied the data that was available, but concluded that it was useless to show valid comparison between the two systems, and that the tests needed to be redone. The second test was carried out in May 1994, and the on-road tests had to follow immediately prior to the full evaluation of the collected test data because the Acurex Environmental CEM was committed to another use. This proved in the end to be a significant problem on the project, because some changes in the test set-up would have undoubtedly been made to improve upon the on-road data that was collected.

The second test proceeded without major events, and substantial amounts of data were collected during the tests. A portion of this data has yet to be evaluated due to funding limitations and the previously described problems which resulted from equipment failures during the on-road testing. Data from two chassis dynamometer tests has been examined and results are presented in Section 6.

The most significant problem encountered during the data evaluation was due to the velocity measurements in the inlet air duct. The measurements appeared suspiciously low at low speed but normal at higher throttle positions. There were also incidences where the measurement seemed completely out of range over short intervals (1 to 2 seconds). It is speculated that water condensation may have impacted the hot-wire anemometer, causing significant signal variations unrelated to either flow velocity or equipment failures.

To attempt to trace these inconsistencies in the measurement, Acurex Environmental conducted a calibration effort of the test section subsequent to the chassis dynamometer tests and on-road tests. A duct and fan were connected to the test section and the anemometer measurement was compared to a pitot reading. The result was the calibration curve shown in Figure 3-10. The anemometers were indeed functioning properly. Further tests bending the inlet duct to the test section, however, also confirmed that very significant stratification could occur in the duct due to bends immediately upstream or downstream of the sensors. This was particularly pronounced at lower velocities, which would explain the very low flow velocity readings during low throttle operation of the engine, i.e., when the turbocharger is not engaged.

The computational program developed earlier in the program proved unable to generate gram-per-mile values from the measured parameters. Nevertheless, alternate methods of analysis were applied to yield positive results as will be presented in Section 6.

5.2 TESTING ON-ROAD

As previously discussed, on-road testing had to be scheduled immediately following the chassis dynamometer tests in order to make the emission measurement system available for other commitments. Under this accelerated schedule, problems were encountered that could have perhaps been avoided.

Figures 5-3 through 5-6 show the final test configuration. In Figure 5-4 the umbilical loops are visible, and in Figure 5-5 the generators are visible. Figure 5-6 shows the ballast containers that

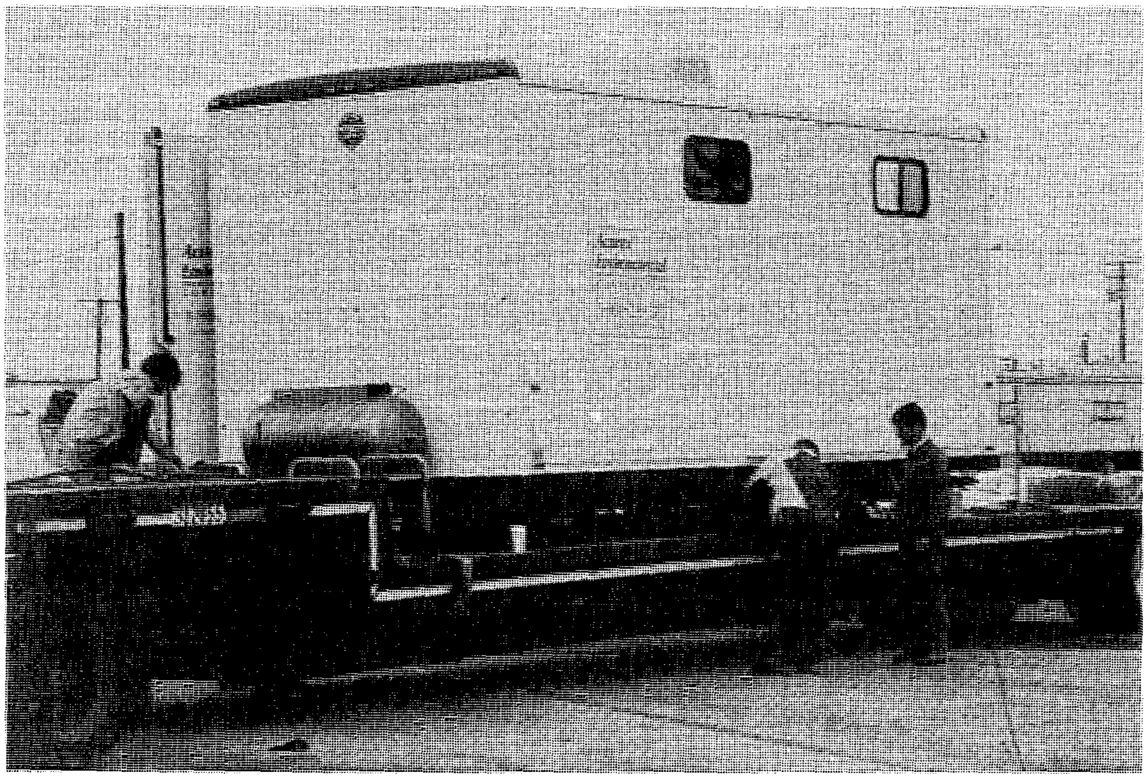


Figure 5-3. Setting up the emissions sampling system trailer for on-road tests

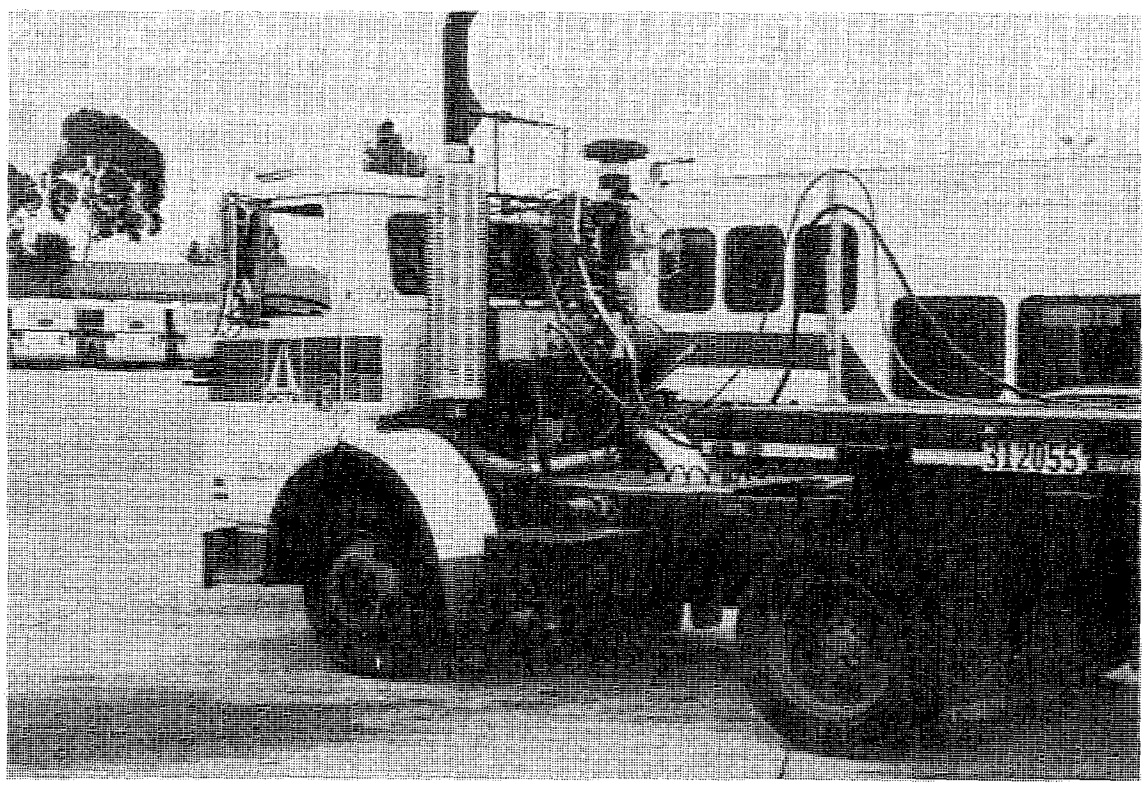


Figure 5-4. Umbilical loops

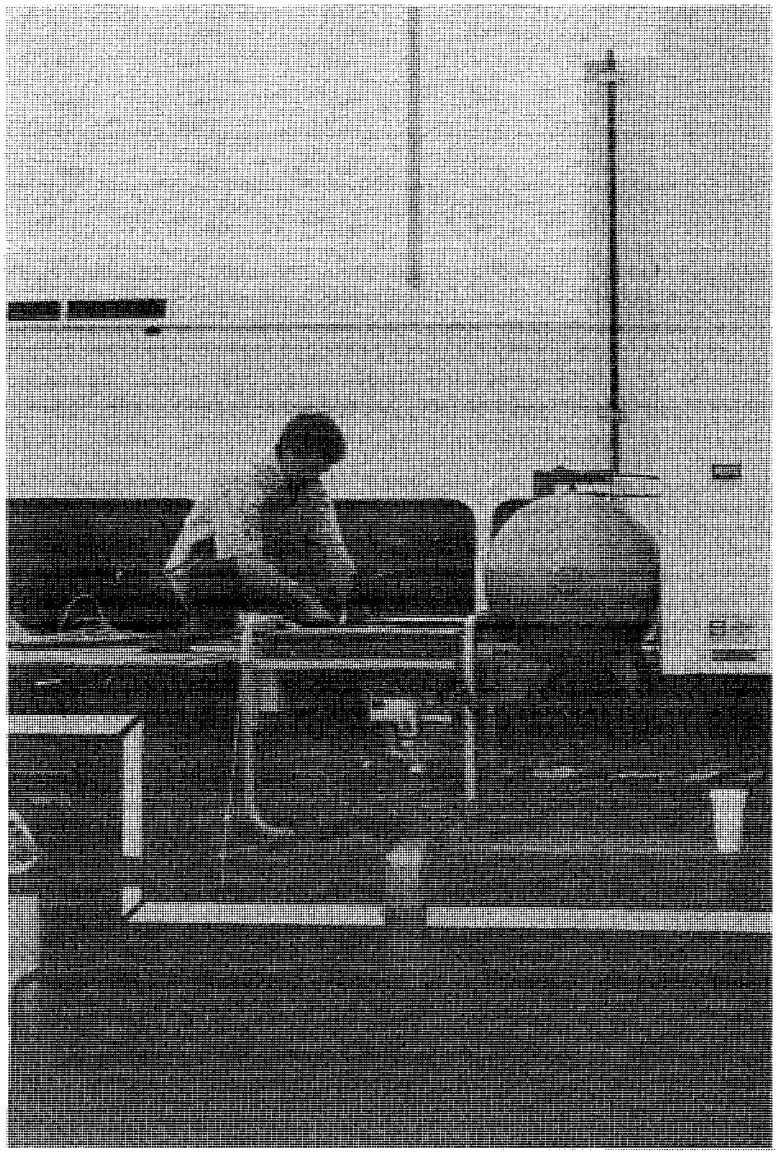


Figure 5-5. The trailer set-up was checked to ensure that everything was secure

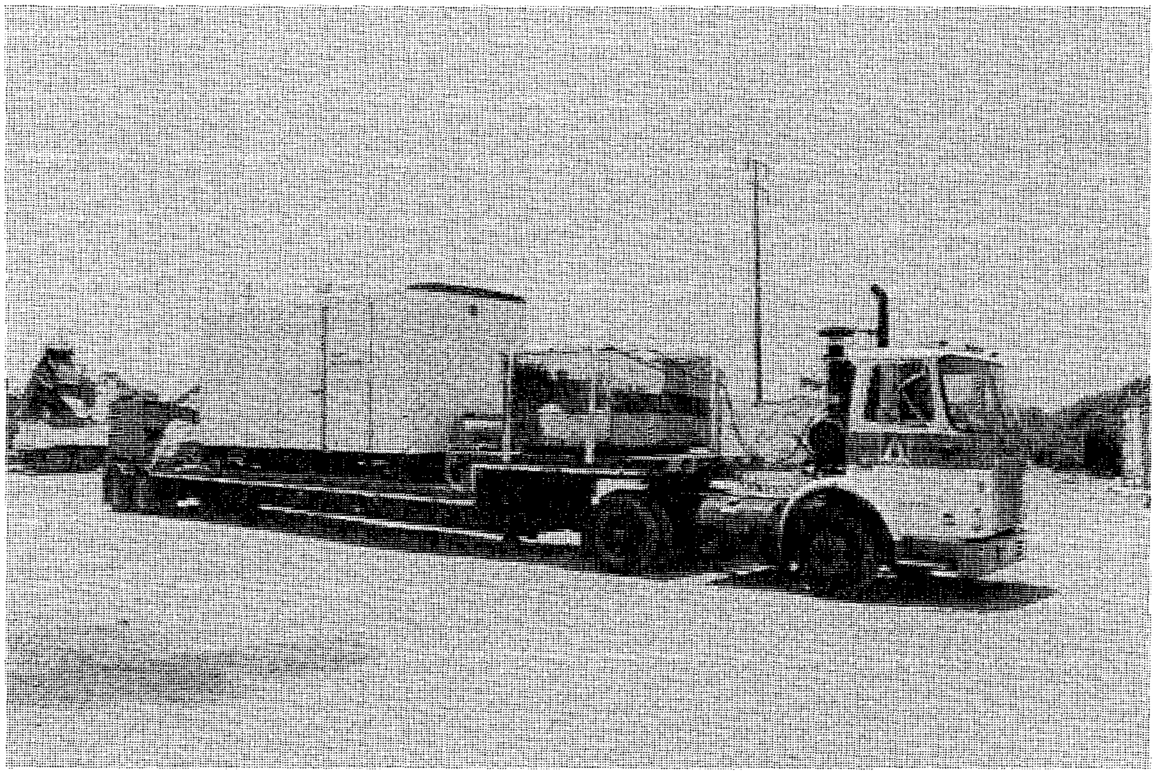


Figure 5-6. Test vehicle configuration showing CEM system and vehicle-weight variation ballast containers

were used to vary the load of the trailer. Load changes were made in the morning prior to the test runs and the load change was verified on local scales.

The problems that were encountered with the power supply have already been discussed in Section 3.

When tests were started, the air conditioner for the trailer failed during a test run and the emissions equipment overheated. Two of the analyzers required servicing because they could no longer be calibrated. This resulted in a test delay.

The final equipment configuration that allowed the tests to proceed included three generator sets, two power conditioners, and one gas fired air compressor. The problems were finally overcome and tests could proceed efficiently.

Additional data, as presented in Appendices B and C, is available for further analysis and reduction. As discussed in Sections 6 and 7, despite the challenges encountered at various points during the dynamometer and on-road testing, this data should still contain important indications of actual in-use emissions from a heavy-duty truck.

SECTION 6

TEST EVALUATION AND RESULTS

6.1 OBJECTIVES

As described in Section 5, complications in the initial testing required that an additional series of tests be performed. Additional funding was procured and funding for data analysis was diverted to cover the additional testing costs. Thus, the data analysis performed was significantly reduced from the initial plan, and a body of data from this project remains to be analyzed.

The following sections describe our approach to evaluating the data collected during testing. Additionally, the sections discuss our successful correlation of the emissions test results from the on-board CEM to the LACMTA ETF system for the two tests for which data analysis has been completed: Test 1055 — a CBD — and Test 1063 — a Commuter Phase. Further work is needed to adequately draw conclusions and to develop a single (or set of) correlation factor(s) that will enable direct comparison of on-board emissions results to those measured by the LACMTA ETF independent of the test (or duty) cycle. The development of such a factor (or set of factors) to compare the results from the CEM and the ETF from the chassis dynamometer tests would allow us to successfully measure emissions with the CEM over the road. With the correlation factor(s), we could be confident that the CEM measurements on the road would be as accurate as the ETF measurements on the chassis dynamometer.

6.2 APPROACH

To correlate the chassis dynamometer emissions results of the CEM to those of the LACMTA ETF, data was taken simultaneously using both sets of equipment. The on-board data acquisition system collected the following information by second

- Engine rpm
- Vehicle pulse
- Throttle position
- Temperature
- Inlet air flow velocity
- Emissions concentrations (in ppm and %)

These parameters were used to calculate parameters for direct comparison of the results measured by the ETF, such as vehicle speed, exhaust flowrate, and mass emissions rate.

6.2.1 Vehicle Speed

Vehicle speed data was used to confirm test timing. To assure the appropriate data was being allocated to a given test, the vehicle speeds measured by both the CEM and the ETF were plotted and matched. The on-board system measured "pulses" which represent rotations of the axle over a period of time. Conversion to vehicle speed was accomplished using equation 6-1.

$$Vehicle\ mph = \frac{pulse}{s} \times \frac{1}{AR}\left[\frac{rev}{pulse}\right] \times \frac{1}{GR} \times C(in.) \times 3600\frac{s}{h} \times \frac{1\ mile}{5280\ ft} \times \frac{1\ ft}{12\ in} \quad (6\text{-}1)$$

where:

C = tire circumference = 114 in. (measured)

AR = axle revolutions = 16 pulses/rev

GR = gear ratio = 3.58

6.2.2 Exhaust Flowrate

Calculation of the exhaust flowrate is critical to the evaluation of the emissions results. The on-board system measured the inlet air flow velocities using two sensors placed across the flow duct (diameter of 17.6 cm). One sensor was placed near the center (8.6 cm from wall), the other was placed 4.8 cm from the wall. The results were expected to show fully-developed turbulent flow; however, a bend in the pipe located upstream of the sensors lead to flow separation which in turn required that we develop adjustment factors for the determination of the exhaust flowrates.

Equation 6-2 shows the general formula for calculating flowrates. Equation 6-3 presents the equation used to estimate the exhaust flowrate measured by the on-board equipment. The flow factors were determined by comparing the on-board estimation to the ETF flowrate, and iterating until these two flowrates were comparable. The iteration of Equation 6-3 was primarily accomplished visually using a time trace of the respective flowrates. Due largely to mixing of the fluid in the ETF dilution tunnel (which smooths instantaneous aberrations) and the inherent imprecision of the air flow velocity measurements, the comparison is, at best, an estimate.

$$\textit{Flow Rate CEM Q (scfm)} = AV\left[\frac{ft}{\min}\right] \times PA\ (ft^2) \tag{6-2}$$

where:

AV = air velocity (ft./min.) as measured by flow sensors 1 and 2

PA = pipe cross-sectional area ($ft.^2$) = 0.2625 $ft.^2$

$$\textit{Factored CEM Q} = \frac{(FF1 \times Q_1) + (FF2 \times Q_2)}{2} \tag{6-3}$$

where:

FF1 = flow factor 1

FF2 = flow factor 2

Q_1 = flowrate calculated from sensor 1 measurement, equation 6-2

Q_2 = flowrate calculated from sensor 2 measurement, equation 6-2

6.2.3 Emission Concentrations

In the dynamometer tests, we monitored modal NO_x ppm, CO ppm, and CO_2 percent. Comparison of the raw results showed, as expected, variation in the dilution ratios of the two systems. From the raw concentration comparison, the impact of the instrument detection delay on measurements is clearly discernable. The on-board instruments have a slower response time, and the sample must travel slightly farther to reach the instrument probes. We later adjusted the test results to account for the time delay. The NO_x analyzer may also have been improperly calibrated.

6.2.4 Emission Rates

Theoretically, the NO_x emission rates measured by both the ETF and the CEM should be the same. Equation 6-4 was used to calculate the emission rate measured by the CEM. The results were then compared to the real-time emissions data provided by the ETF computer printouts. A correction factor, accounting for poor instrument response and calibration errors, was used to adjust the calculated on-board NO_x measurement to match the ETF results.

$$NO_x\ (g/s) = Q_{out}\ (scfm) \times NO_x\ \rho\ (g/ft^3) \times \frac{NO_x}{10^6\ ppm} \times CCF_{NO_x} \times \frac{1\ \text{min}}{60s} \qquad (6\text{-}4)$$

where:

Q_{out} = exhaust flowrate, from equation 6-3

$NO_x\ \rho$ = NO_x density = 53.96 g/ft^3

CCF_{NO_x} = calibration correction factor for NO_x analyzer (dimensionless)

Ideally, the factors used to match the emission rates of the CEM and the ETF equipment would be independent of test cycle or duty cycle. Because of the limited amount of data analysis that could be accomplished, however, this "closing of the loop" has not yet been performed. The following section compares the data analysis results from the two tests evaluated.

6.3 DATA ANALYSIS RESULTS

The first test analyzed was a CBD cycle, to enable comparison of the transient testing capabilities of the two monitoring systems. The weighted average of the flowrate from the CEM is shown in Figure 6-1, compared to the flowrate measured by the ETF. The weighted flowrate, calculated from equations 6-2 and 6-3, appears to correlate well with the flowrate measured by the ETF. The vehicle speed measurements from the CEM, measured in pulses, also matched very well with the ETF data. This is plotted in Figure 6-2.

Comparison of the modal NO_x emissions data from the CEM and from the ETF revealed that the time delay of the CEM NO_x analyzer was about 50 s, as seen in Figure 6-3. Figure 6-4

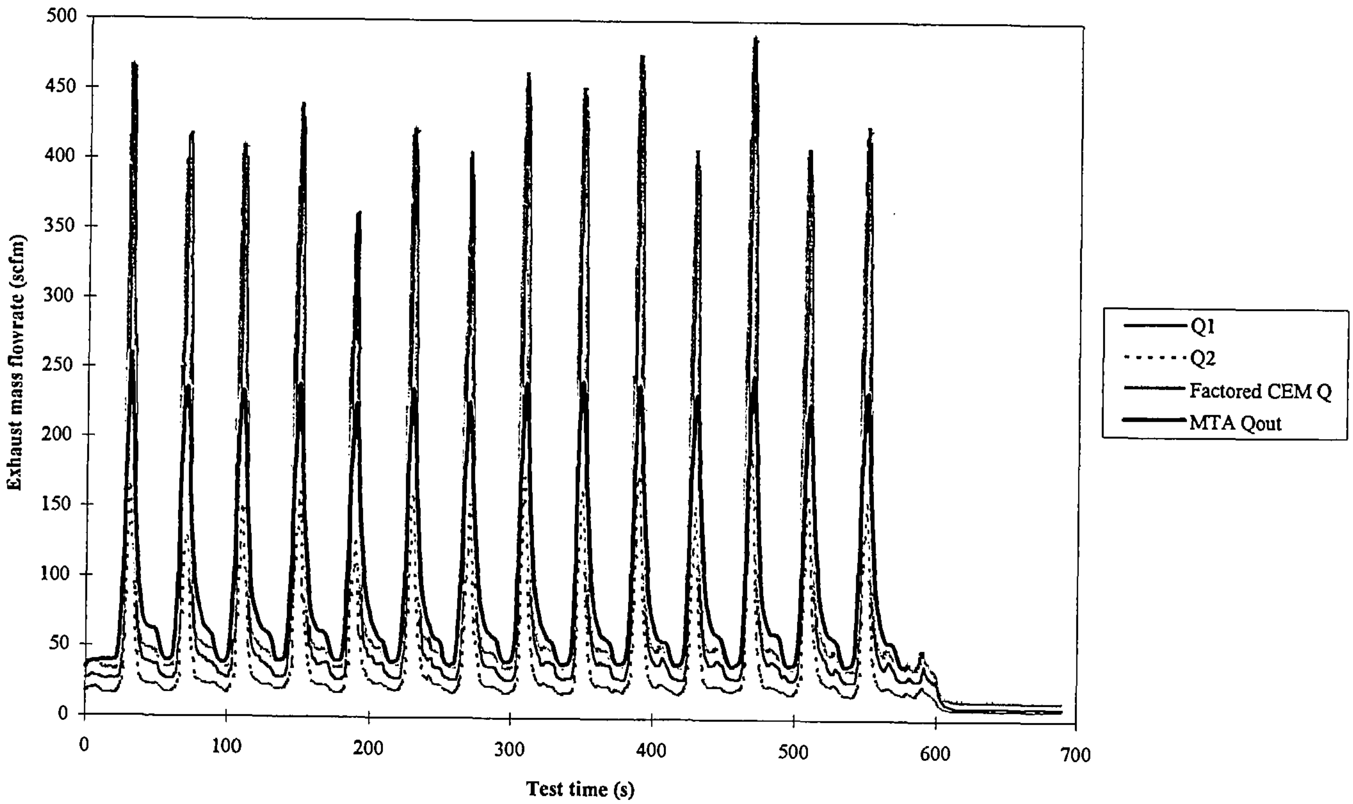


Figure 6-1. Exhaust flowrate, Test 1055, CBD, May 9, 1994, 11:46 a.m.

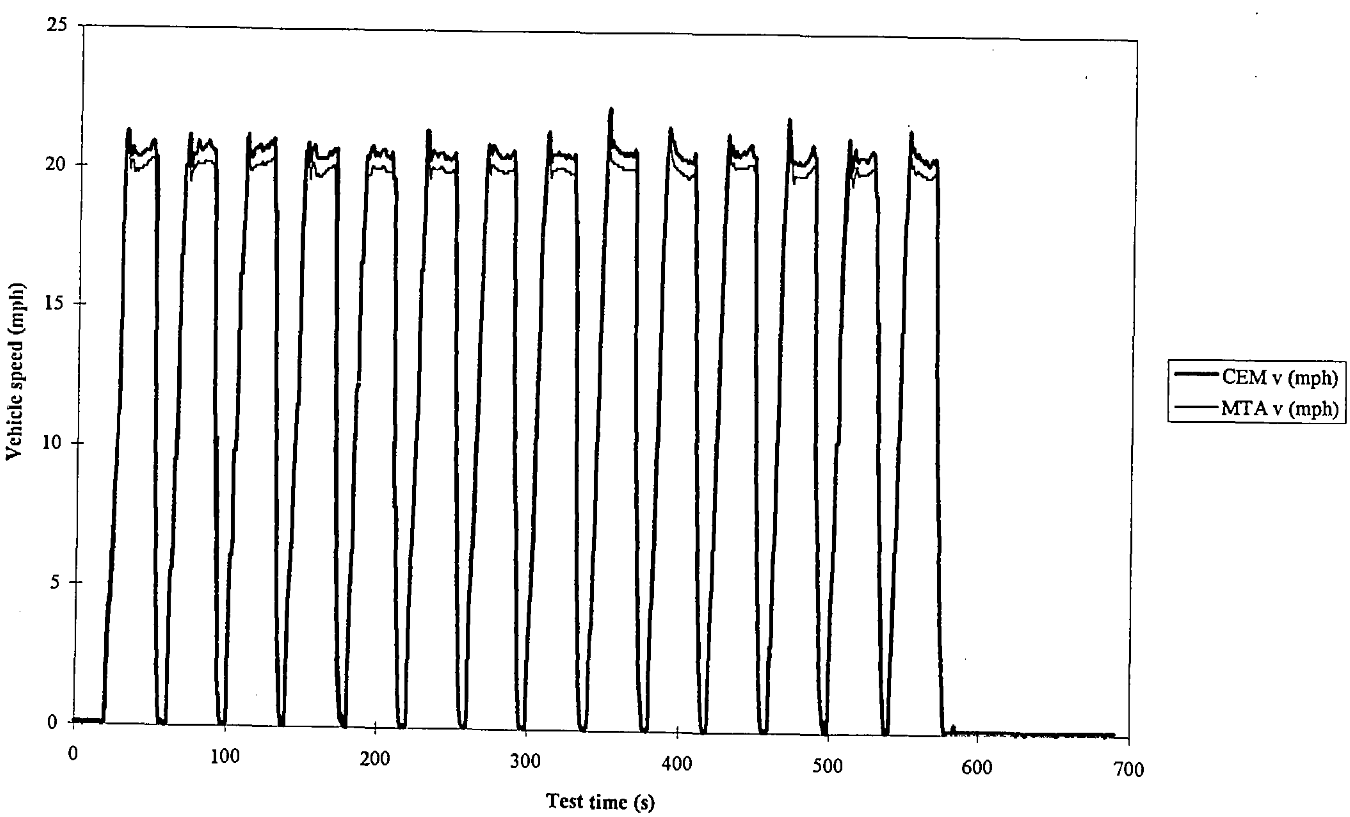


Figure 6-2. Vehicle speed, Test 1055, CBD, May 9, 1994, 11:46 a.m.

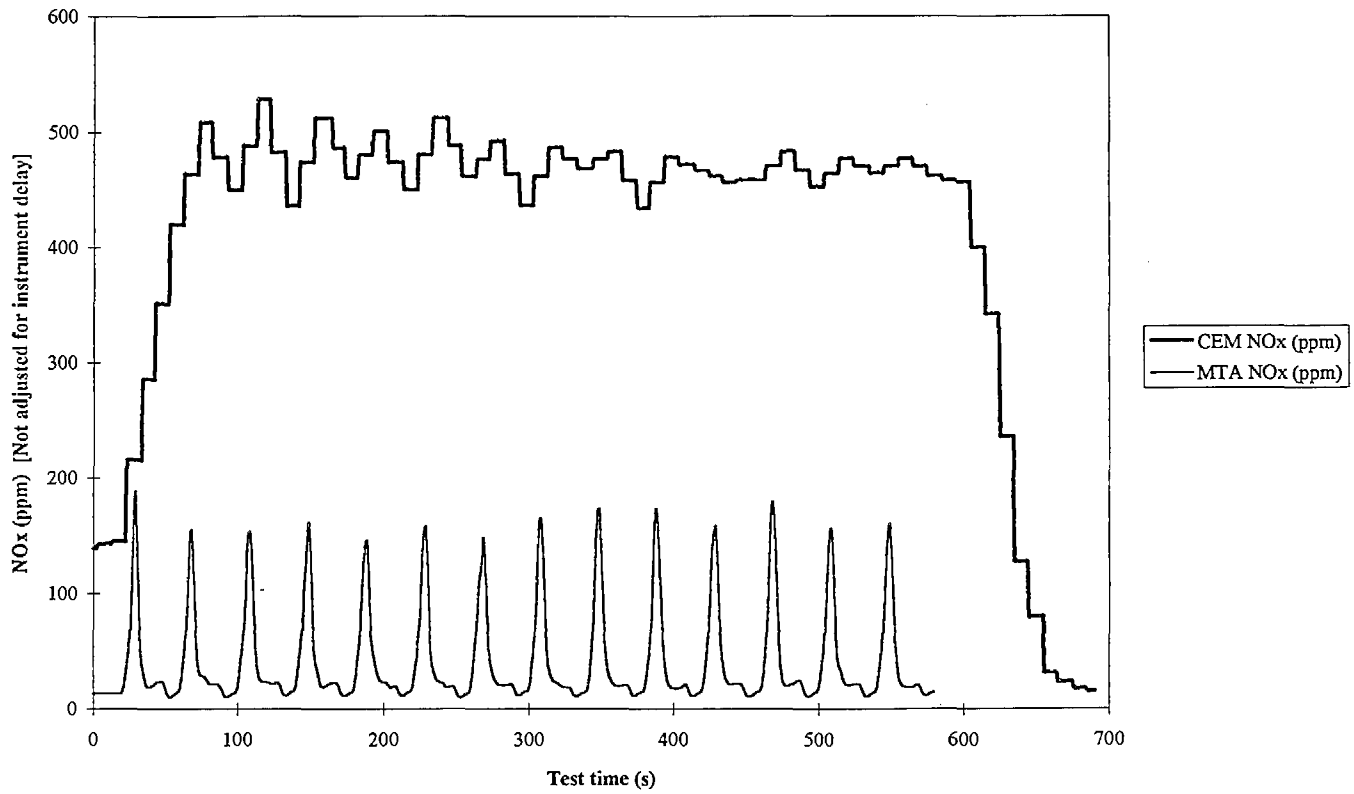


Figure 6-3. NO_X ppm, Test 1055, CBD, May 9, 1994, 11:46 a.m. (not adjusted for time delay)

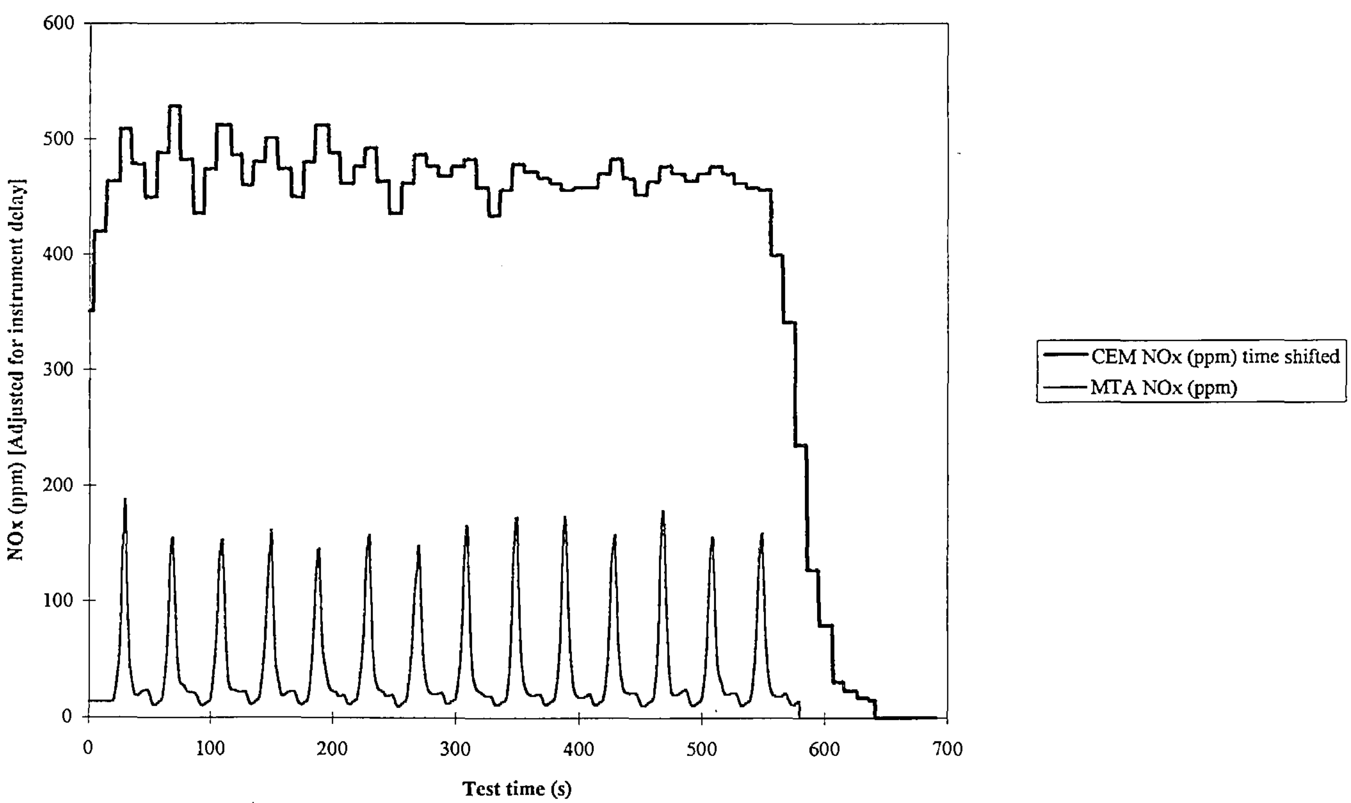


Figure 6-4. NO_X ppm, Test 1055, CBD, May 9, 1994, 11:46 a.m. (adjusted for time delay)

shows the modal NO_x ppm trace with the CEM trace shifted approximately 50 s to the left. Both the CEM and the ETF analyzers used a diluted sample; the CEM, however, used a higher, constant dilution ratio of 100:1, whereas the ETF used a variable dilution ratio. The ppm traces from the CEM shown in Figure 6-3 and Figure 6-4 already have the dilution ratio factored in, whereas the ETF traces do not, which explains why the CEM concentration appears so much higher.

In order to determine the NO_x mass emission rate, the problems with the NO_x analyzer had to be corrected for. One of the problems, which can be seen in Figure 6-4, is a significant damping effect. The cause of this is not known. The correction factor in equation 6-4 produces a mass emission rate that is in very good agreement with the ETF emission rate.[1] This can be seen in Figure 6-5. The cumulative mass emissions from both sets of data also follow each other very well, as seen in Figure 6-6.

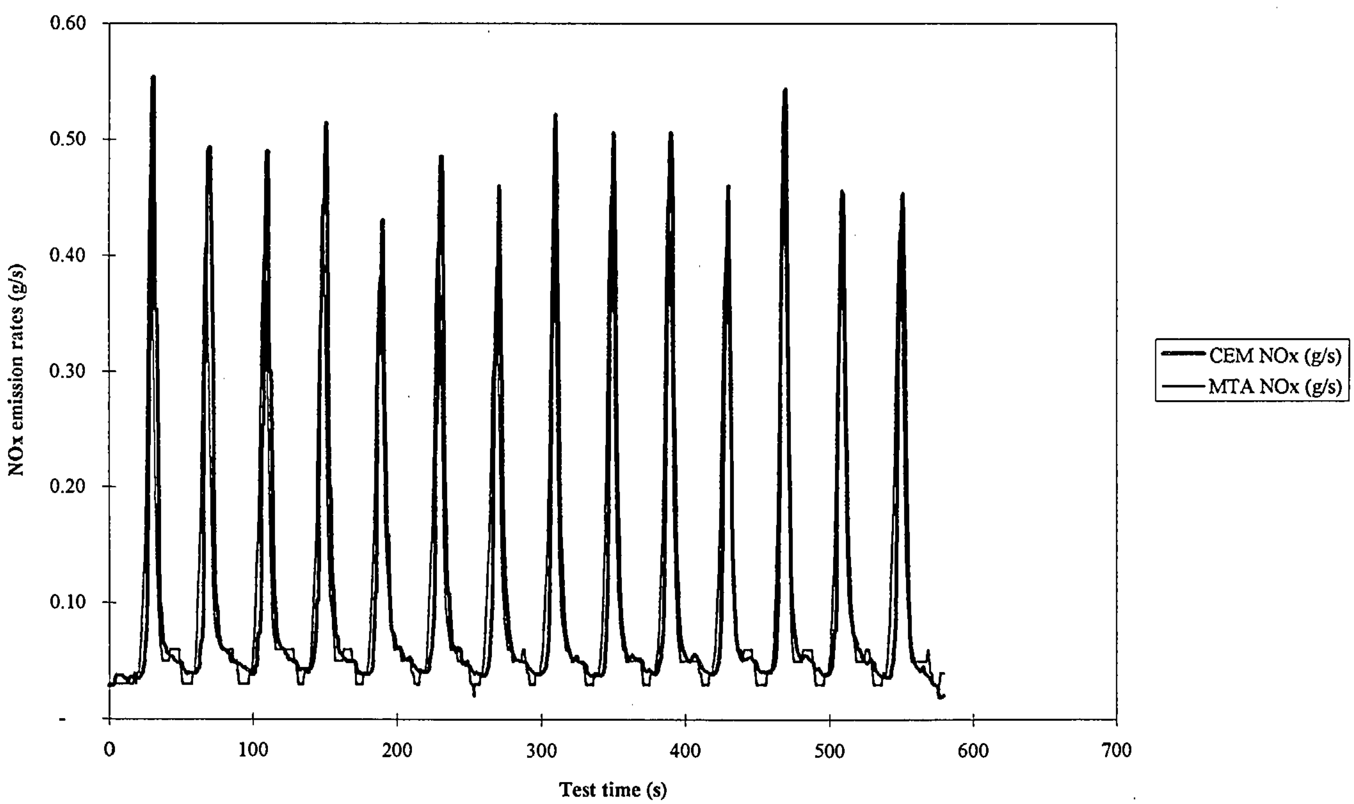


Figure 6-5. NO_x (g/s), Test 1055, CBD, May 9, 1994, 11:46 a.m.

[1] If there had been no problems with the NO_x analyzer, a NO_x correction factor would not be necessary. The adjustment factors for the flowrate would have been all that was needed to accurately calculate the mass emission rate.

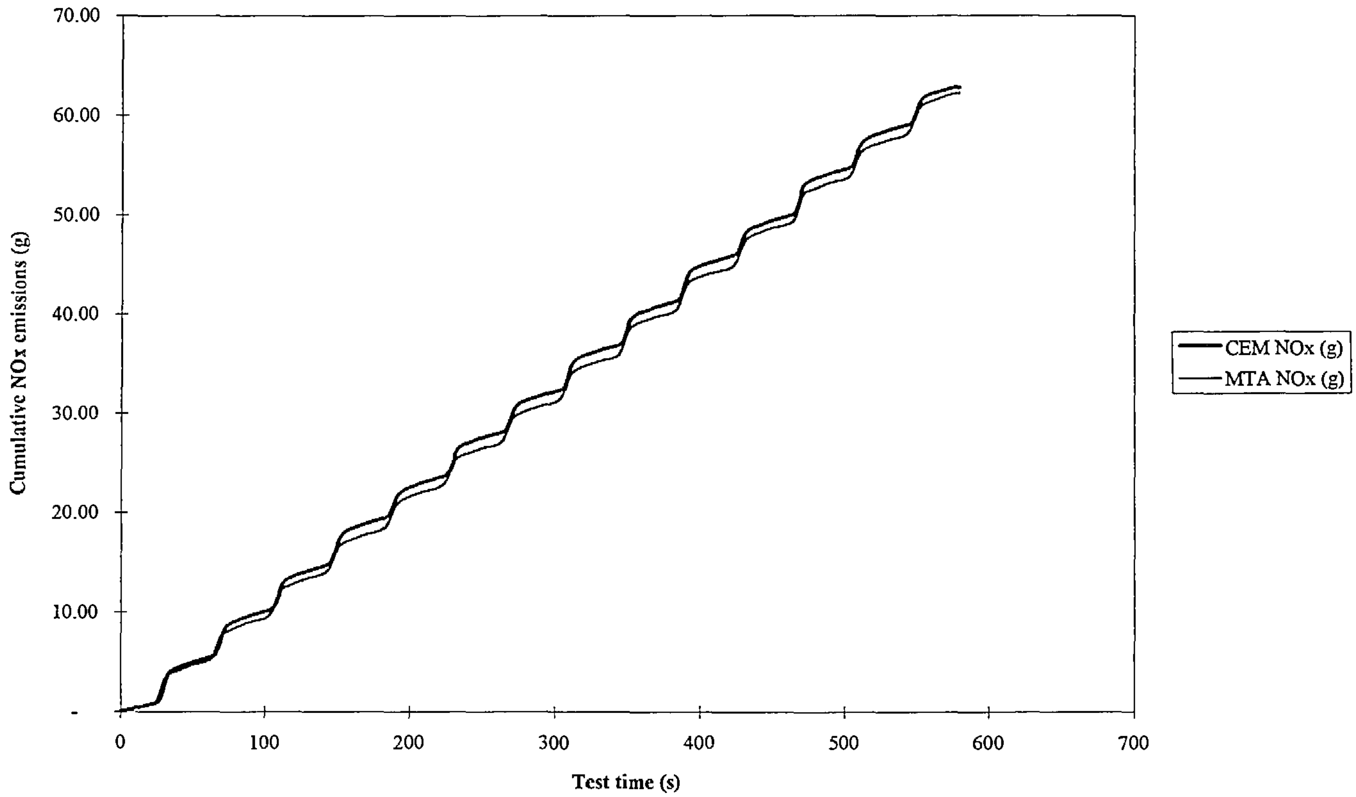


Figure 6-6. Cumulative NO_x (g), Test 1055, CBD, May 9, 1994, 11:46 a.m.

The second test analyzed was a commuter phase cycle to evaluate the steady-state measuring capability of the CEM system as compared with the ETF. Most of the duration of the commuter test cycle involves a steady-state cruise at 55 mph. It was hoped that the correction factors developed for test 1055 could also be applied to test 1063, or any other test cycle, to yield results that would be in agreement with the ETF results. Unfortunately, the data anomalies that the correction factors were intended to adjust varied from test to test, and thus could not all be satisfactorily adjusted with common correction factors.

The plot of flowrate versus time for test 1063 is shown in Figure 6-7. The correction factors developed for this data produce a curve that generally follows the same trends as the ETF curve, although the ETF curve is much smoother than the CEM curve. The CEM flow sensors have good resolution, thus the sharp peaks and troughs of the CEM curve should accurately represent the flowrate. The ETF, on the other hand, calculates the flowrate from the CO_2 concentration, which

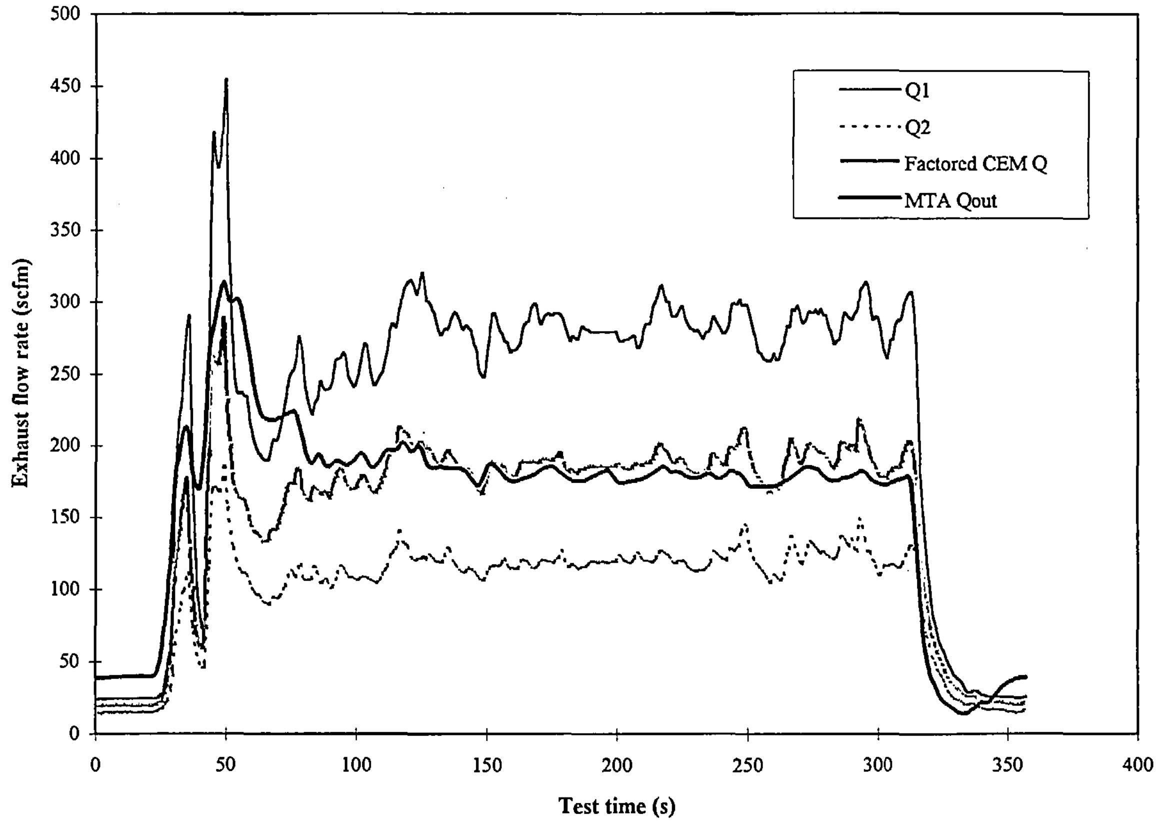


Figure 6-7. Exhaust flowrate, Test 1063, Commuter, May 19, 1994, 10:57 a.m.

may be less accurate. There may have also been a separation of flow upstream of the hot wire anemometer sensors in the CEM, so that during some of the early segments of the test at low speed, the anemometers were unable to sense any flow. It was difficult to derive one set of correction factors that could effectively adjust the inconsistencies during all portions of the test. One set may better correct the data during the acceleration portion, for example, but not during the cruise portion, and vice versa. Since the commuter test is concerned with steady-state operation, it was deemed more prudent to use correction factors that would be most accurate for the cruise portion of the test, rather than for the acceleration portion.

As with test 1055, there were no problems with the vehicle speed calculations from the CEM data. The speed trace is shown in Figure 6-8. All fixed parameters in equation 6-3 are the same for test 1063 (and for all remaining tests as well).

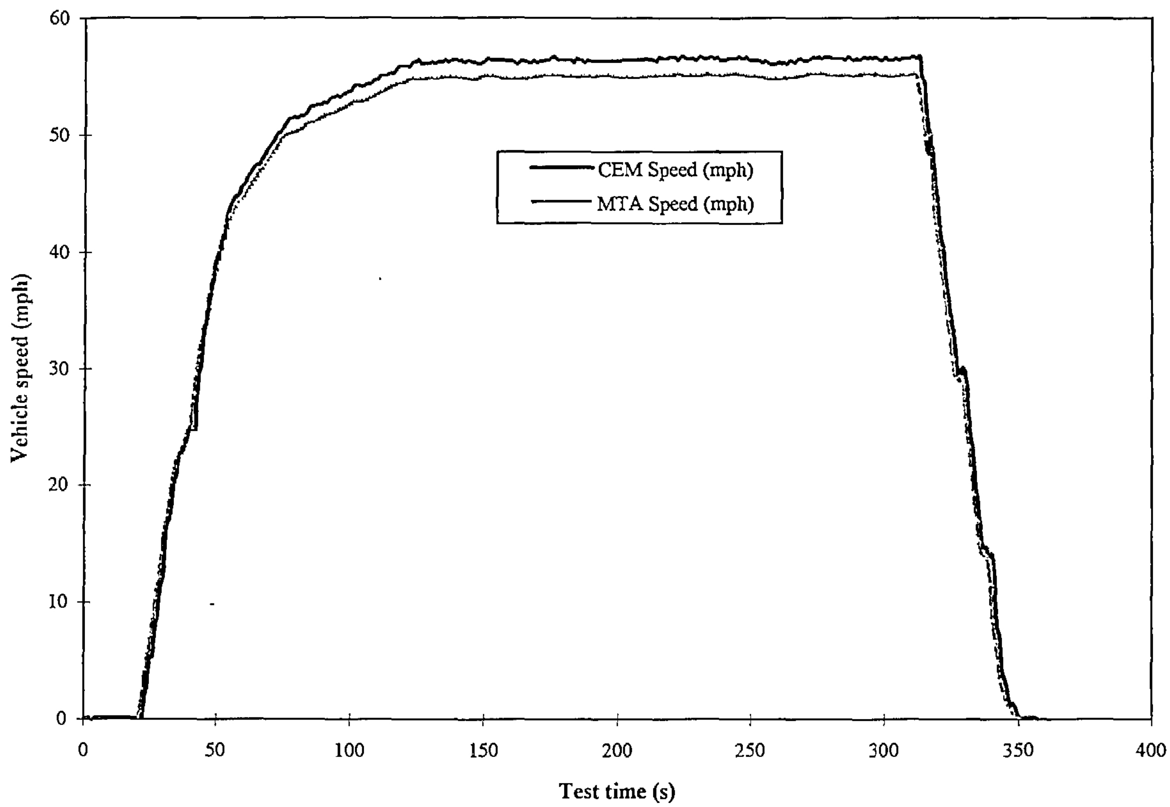


Figure 6-8. Vehicle speed, Test 1063, Commuter, May 10, 1994, 10:57 a.m.

Figures 6-9 and 6-10 show the NO_x ppm levels versus time before and after the adjustment for the instrument time delay. These traces look promising, in that they follow similar trends in their peaks and valleys, although the CEM trace does take longer to level off during the cruise portion of the test. This is probably due to slower response times of the CEM NO_x analyzer.

The NO_x mass emission rate, which is shown in Figure 6-11, was calculated from equation 6-5. The cumulative mass emissions are shown in Figure 6-12. The same reasoning used in deriving the correction factors for flowrate was used here as well. The correction factor should be most sensitive to the discrepancies in the cruise portion of the test, since that is the area of interest. The final results of both tests are presented in Table 6-1 below.

Equation 6-5 shows how the mass emission rate was calculated from the raw data:

where:

FF1, FF2 = flow factor for flow sensors 1 and 2 respectively

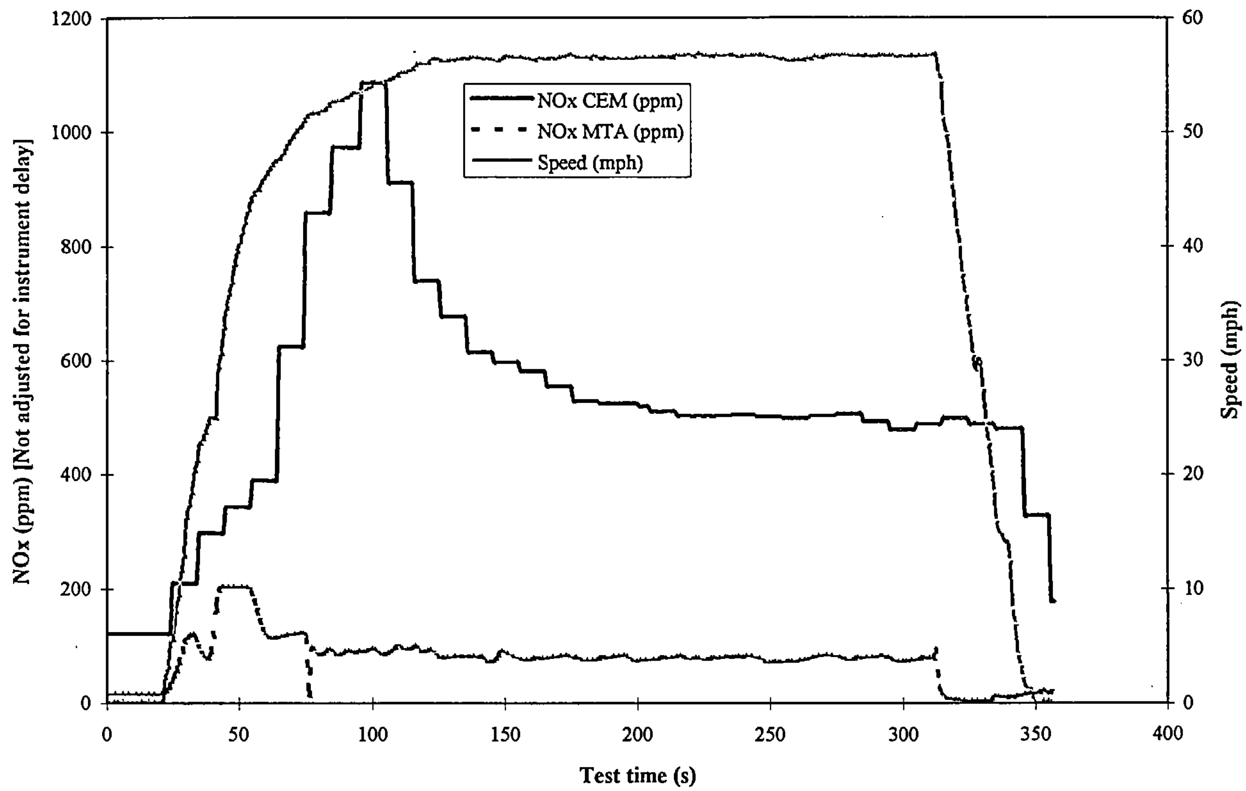


Figure 6-9. NO_x ppm, Test 1063, Commuter, May 10, 1994, 10:57 a.m. (not adjusted for time delay)

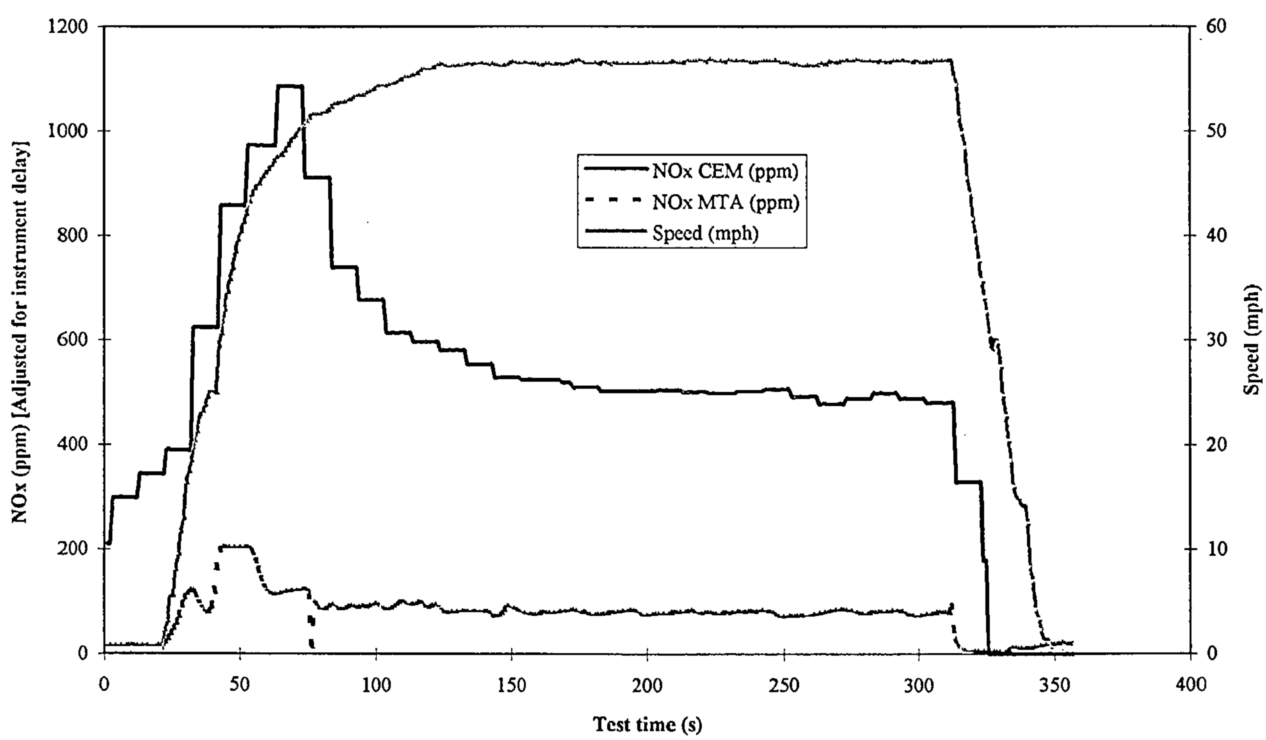


Figure 6-10. NO_x ppm, Test 1063, Commuter, May 10, 1994, 10:57 a.m. (adjusted for time delay)

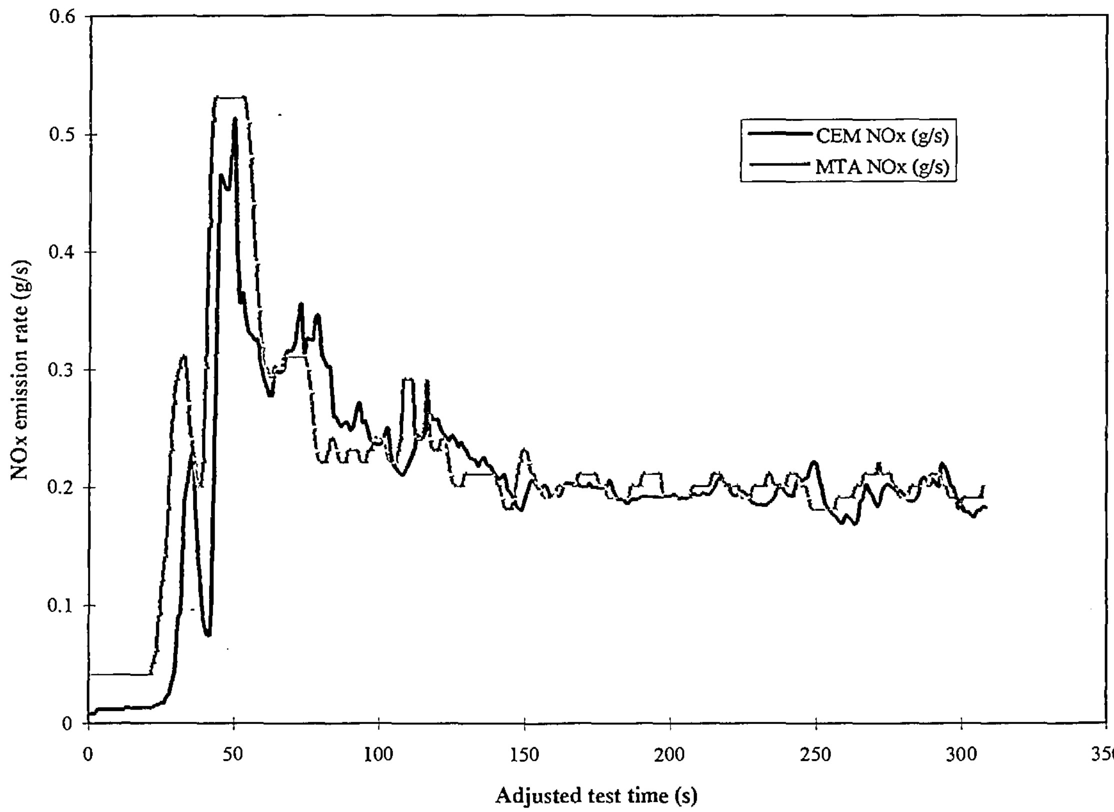


Figure 6-11. NO_x (g/s), Test 1063, Commuter, May 10, 1994, 10:57 a.m.

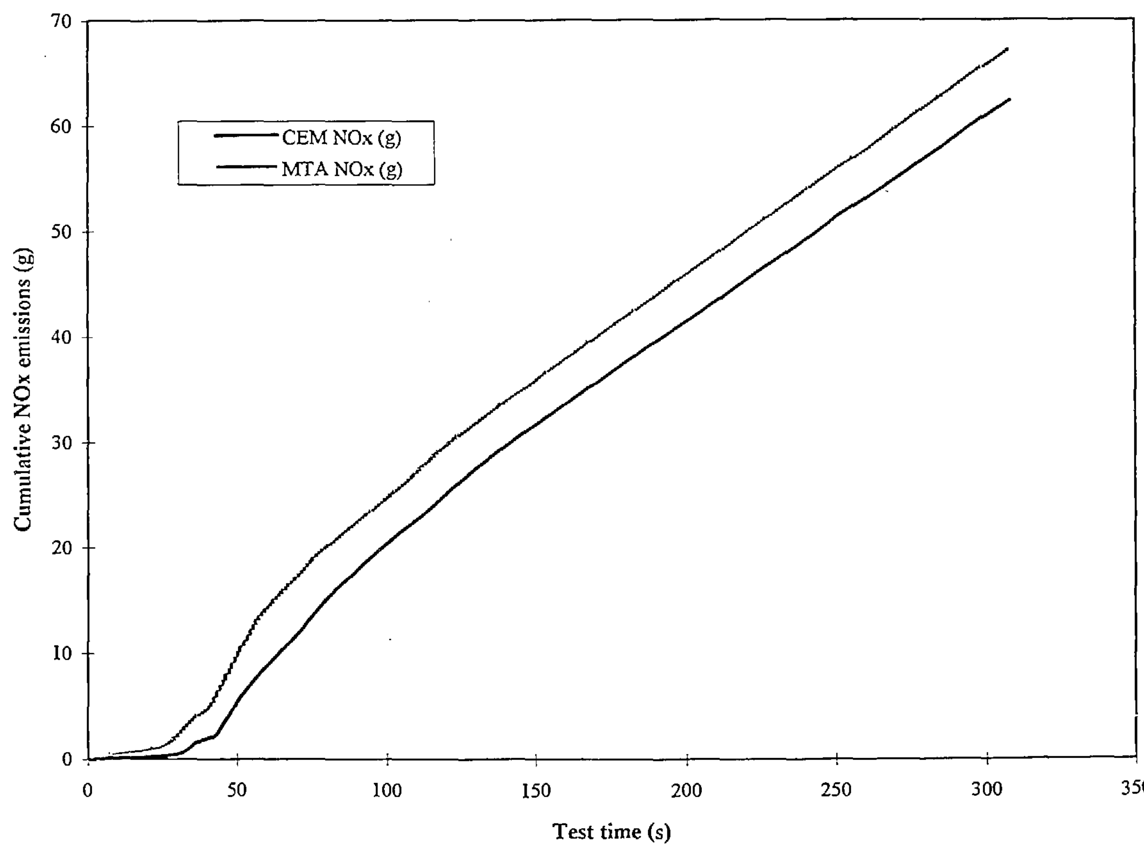


Figure 6-12. Cumulative NO_x (g), Test 1063, Commuter, May 10, 1994, 10:57 a.m.

Table 6-1. Summary of results of Tests 1055 and Test 1063

Parameter	Test 1055 — CBD	Test 1063 — Commuter Phase
FF1	1.3	0.6
FF2	2.0	1.5
CCF_{NOx}	2.6	2.3
g/mile CEM	2.17	14.15
g/mile ETF	2.18	15.98

$$NO_x \left[\frac{g}{s}\right] = \frac{[(FF1 \times AV1) + (FF2 \times AV2)]\left[\frac{ft}{\min}\right] \times PA\ (ft^2)}{2} \times NO_x\,\rho \left[\frac{g}{ft^3}\right] \times \frac{ppm\ NO_x}{10^6} \times CCF_{NO_x} \times \frac{1\ \min}{60s} \qquad (6\text{-}5)$$

AV1, AV2 = air velocity from sensors 1 and 2 respectively

PA = pipe cross-sectional area ($ft.^2$) = 0.2625 $ft.^2$

$NO_x\,\rho$ = NO_x density = 53.96 g/ft^3

CCF_{NO_x} = calibration correction factor for NO_x analyzer

A short segment of the on-road data was briefly analyzed to see how it would compare with the CEM dynamometer data. These results are shown in Figures 6-13, 6-14, and 6-15. To calculate the mass emission rate for this segment, we used the correction factors developed for the Commuter Phase test, since most of this on-road segment occurs around 60 mph. The calculated NO_x emissions were 45.4 g/mile, significantly higher than the values determined from the dynamometer tests.

6.4 CONCLUSIONS

As of the completion of these preliminary analyses, the comparison of onboard and chassis dynamometer emission testing shows promise. In each test evaluated, conversion factors were identified that overcame variations in the measurement techniques and instruments. Factors such

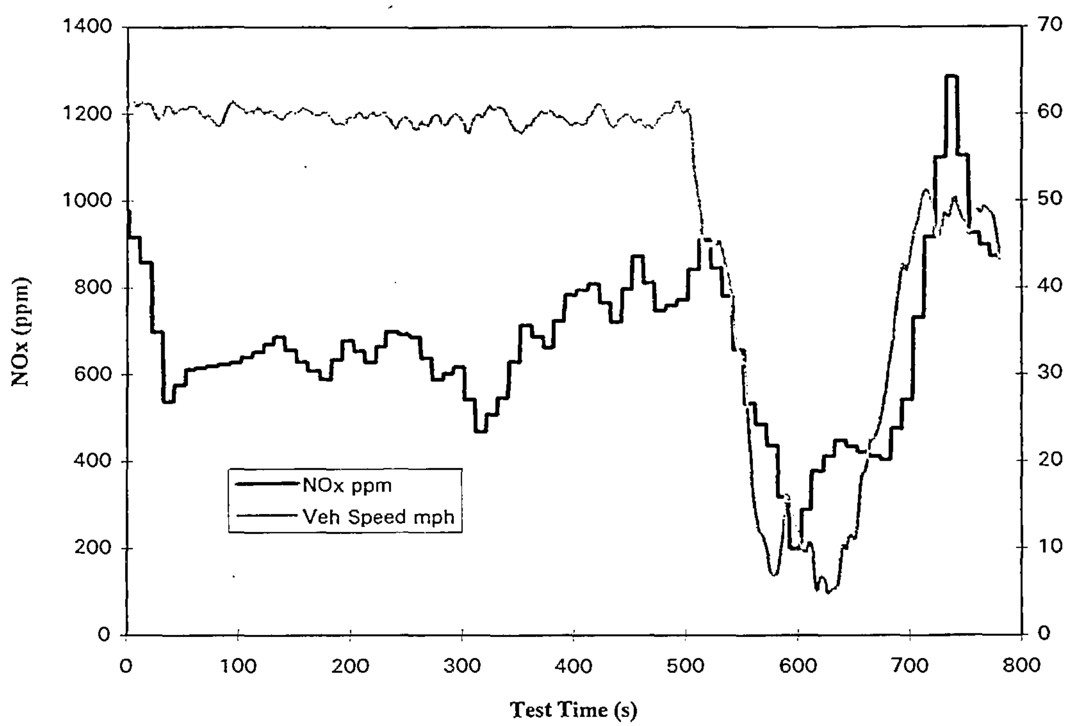


Figure 6-13. On-road test, June 28, 1994, heavy afternoon traffic on 405 Freeway in Los Angeles

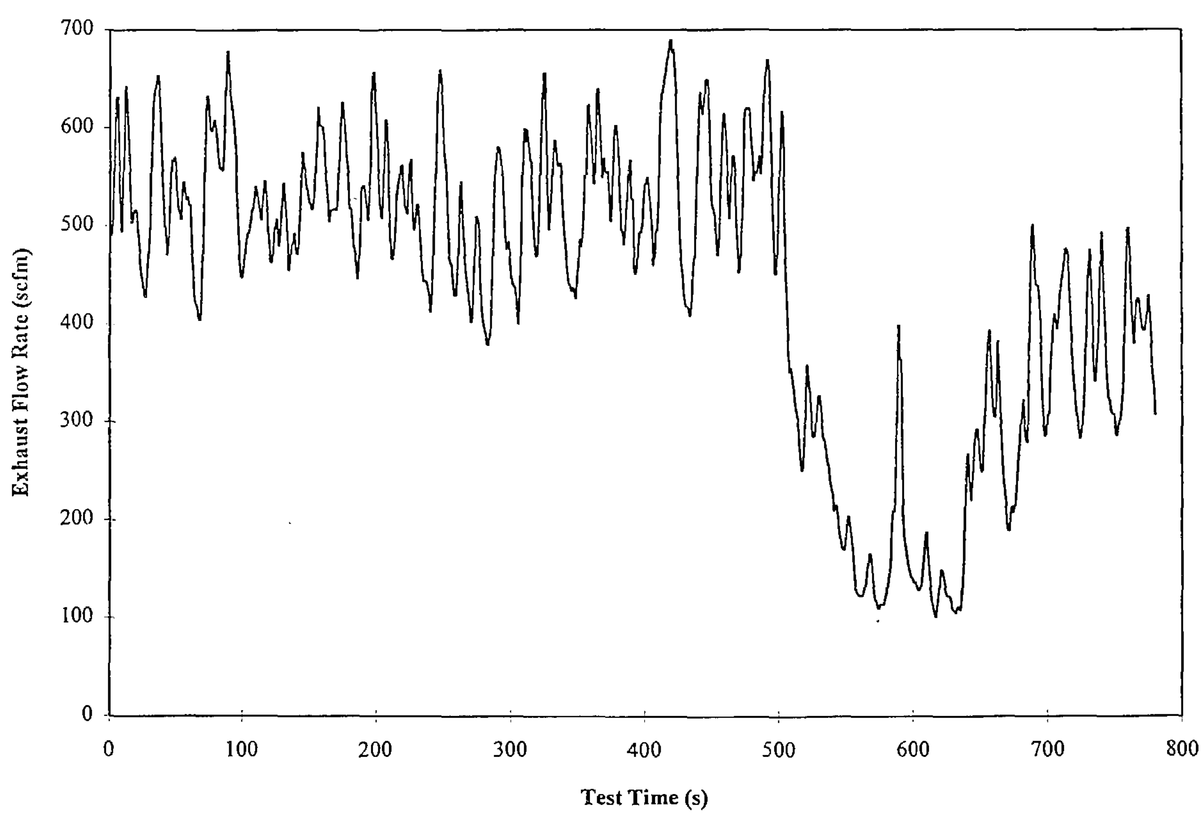


Figure 6-14. Exhaust flow rate, on-road test, June 28, 1994, heavy afternoon traffic on 405 Freeway in Los Angeles

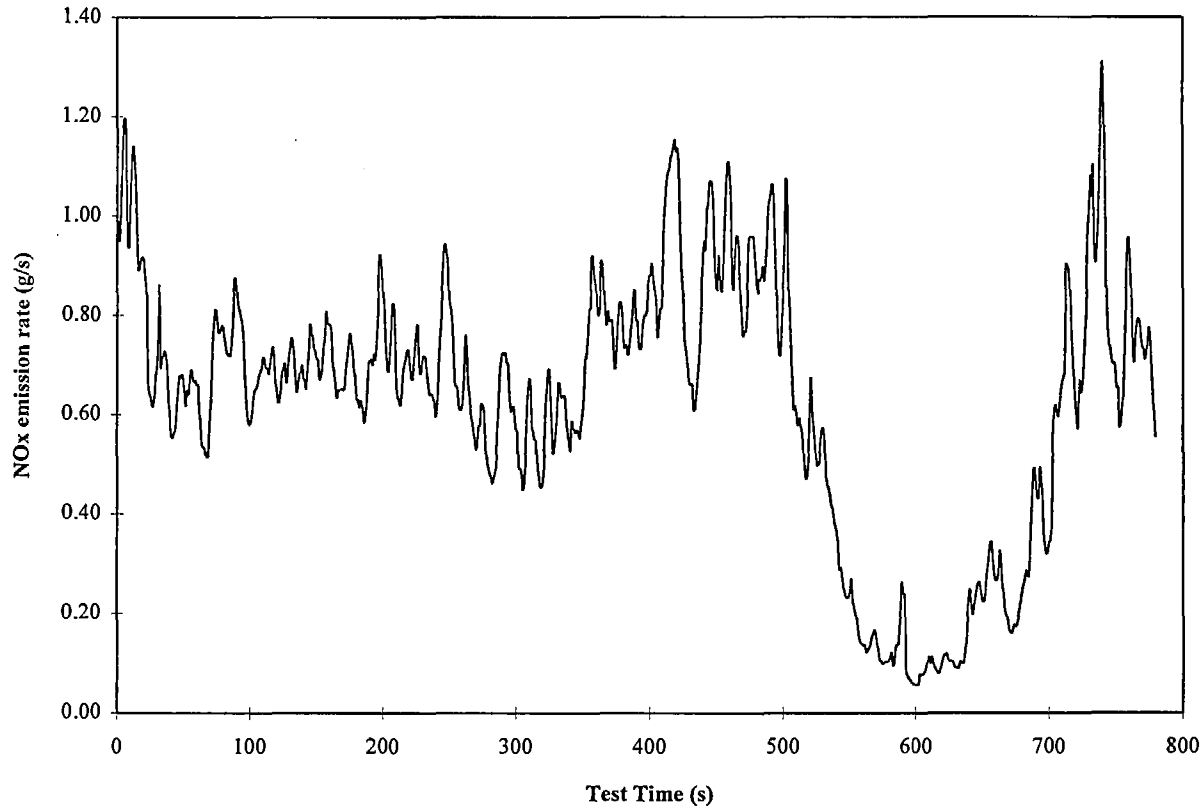


Figure 6-15. NO_x (g/s), on-road test, June 28, 1994, heavy afternoon traffic on 405 Freeway in Los Angeles

as instrument response time, calibration, mixing, flowrate measurement and dilution were successfully addressed for each test.

Further work is necessary to verify the applicability of the factors identified to other test cycles. Additionally, the development of a single (or set of) factor(s) to be used for comparison of emissions measurements independent of test or duty cycle would greatly advance the potential use and value of the on-board emissions testing system.

SECTION 7

RECOMMENDATIONS FOR FURTHER WORK

7.1 PROJECT OBJECTIVES AND ACCOMPLISHMENTS

The overall goal of this project was to demonstrate a technology that could be used to aid air pollution control agencies and other concerned parties in developing accurate emissions inventories. It could also provide a profile of what areas of the transportation sector were contributing the most to the inventory, which would be valuable in developing and implementing emission reduction measures. This could maximize the emission reduction benefit, both from an air quality and an economic standpoint.

Acurex Environmental developed an emissions measuring hardware system that can be installed on-board a heavy-duty vehicle to monitor the real-time in-use emissions while the vehicle is driving on the road over a normal route. The concept was developed from the same continuous emissions measuring (CEM) technology used to monitor stationary sources. The system monitors real-time exhaust gas concentration, engine air flow, and other engine operating parameters such as engine speed, temperature, and throttle position. The continuous grams-per-mile can be calculated from the exhaust gas concentration and the exhaust air flow.

The system was first tested on a chassis dynamometer at the LACMTA Emissions Testing Facility (ETF). The tests were run in parallel with the ETF system, so that the two systems could be compared. The dynamometer tests were intended to prove that the Acurex Environmental CEM system could measure the grams-per-mile as accurately as the ETF system. The CEM system was later tested over four days of on-road tests. Data analysis of the dynamometer tests was intended to be completed before the on-road tests began, in order to correlate the data from the CEM with the data from the ETF, and to develop necessary correction factors before beginning the on-road tests. Unfortunately, due to scheduling problems, the on-road tests had to be performed sooner than originally planned, and the data analysis was not initiated prior to these tests.

Two main problems were encountered which did not allow for a thorough analysis of the data. The first problem was a failure of the data acquisition systems during the chassis dynamometer tests, both on the CEM and on the ETF. As a result, the data collected was not reliable, and all of the tests had to be repeated. Thus, the testing portion of the project budget was exceeded, leaving insufficient funds to complete a rigorous analysis of the data. The second problem was that the data analysis was not performed until after the on-road test portion was completed. It would have been ideal to have some knowledge of how the CEM and ETF systems compared before beginning the on-road tests.

Limited data analysis was completed on two dynamometer test cycles, a CBD and a Commuter Phase cycle. The raw NO_x concentration data from the two systems did show very similar trends over time, but the CEM NO_x analyzer experienced a delay in detecting the sample and exhibited poor modal response time. The detection delay was probably due to the longer travel path along the exhaust duct to the CEM NO_x probe, which was further along in the duct than the ETF NO_x probe. The poor response time of the instrument is evident from the flat sections in Figures 6-3, 6-4, 6-9, and 6-10. The reason is that this instrument was adapted from a stationary source monitor, where such fast response time is not essential. However, the technology certainly exists to refine this instrument for second-by-second response.

The flowrate data did not compare very well between the CEM and the ETF, which could have been caused by a number of factors. Suspected causes are fluctuations in the flow regime, possible flow separation in the duct, a problem with the ETF computational algorithm, which calculates flowrate from CO_2 concentration in the exhaust, or possibly water condensation on the CEM hot wire anemometers, resulting in unusual spikes in the data. We were able to derive correction factors for the flowrate and the NO_x concentration that produced an acceptable mass emission rate and gram-per-mile result. However, the factors were different for each test, and it is not certain if they can be applied to other tests of the same load cycle, or if they are specific to those tests.

7.2 RECOMMENDATIONS

There are still considerable amounts of data, both dynamometer and on-road data, that merit further analysis. Developing a successful on-road emissions measuring system is a worthwhile venture because of the substantial improvement in the emissions inventory that stands to be gained if the technology can be proven. The next step would be to verify the data analysis technique described in Section 6 through the comparison of additional tests, test cycles, and inertial weight results that were performed on the LACMTA dynamometer and the on-board equipment. The most desired outcome of the data correlation would be to develop a single set of correlation factors that could be applied to any duty cycle. This may not be possible with the current set of data since there were some data discrepancies between different test cycles which may have resulted from instrument failure. With corrections of the instruments and improvements to the flow measurement methods, the CEM approach should prove feasible and reliable. Unfortunately, not enough test data could be analyzed to prove or disprove this theory. This method should be pursued, however, since this would provide the simplest way of correlating on-road emissions measurements to emissions measurements from chassis dynamometer test cycles. At this point, however, there is not enough conclusive evidence from the data analysis to state whether or not a universal set of correlation factors is possible. If future tests are undertaken, a refinement of the emissions measuring instrumentation to provide faster response time, improved air flow or exhaust flow measurement, and more accurate monitoring of engine parameters could eliminate most of the anomalies that were experienced with these tests.

If a single set of factors does not appear feasible, it may be possible to derive correction factors for each type of duty cycle, such as the CBD, the Commuter Phase, and the EPA Schedule D. The factors derived for test 1055 should be applied to other CBD tests in the test matrix, such as tests 1053 and 1054, and likewise, the factors developed for test 1063 should be applied to other commuter tests, such as tests 1064 and 1065, to see how adaptable they are to other tests. Additional correlation factors should be determined for a Schedule D test as well.

On-road test data has not yet been analyzed. It is not likely that most of the speed patterns or engine loads of the on-road tests will match those of any of the dynamometer test cycles. A small segment of the on-road data is shown in Figure 6-13 as an example. This figure shows the ppm NO_x and the vehicle speed versus time for a period of operation in heavy rush-hour freeway traffic. It may be possible to correlate segments of on-road tests with similar segments of dynamometer tests, and to apply the correlation factors from each related dynamometer test cycle to the related segment of the on-road test. If it is possible to develop a single set of correction factors that are applicable to all duty cycles, than the segmented analysis of the on-road tests would not be necessary.

7.3 FUTURE TECHNOLOGY APPLICATIONS

If the objective of this project can be proven with further data analysis and/or instrument refinements, the technology could become a very beneficial tool in understanding and improving air quality, particularly in areas such as the South Coast Air Basin, where the air quality problem is so acute. Current chassis and engine dynamometer test cycles do not accurately represent the real-world load patterns of many heavy-duty vehicles. Engine certification emission levels are based on the results of engine dynamometer tests, which only simulate a very limited range of the engine's possible operations. The number of vehicle types and applications for which a single engine could be optimized are so numerous that it is not cost-effective for the engine manufacturers to certify the emission levels of each combination. Thus the engine certification emission levels may be far below what the engine actually emits in-use. As a consequence, emissions models tend to underestimate the true emissions inventory in a particular region.

Once the technique is completely validated, the on-board emissions measuring technology could be used to characterize typical emissions profiles for different types of heavy trucks in their various applications. For example, the on-board system could be used to test a sample of refuse collection trucks on their normal routes. Refuse collection trucks operate in both urban and residential areas, and experience multiple stops and starts with increasing vehicle weight, as well as extended periods of both engine idle and power-take-off operation during a typical route. Existing dynamometer test cycles do not simulate this type of operation. A sample of transit buses (both intra- and inter-city), a sample of delivery vans, and a sample of long-haul trucks are other vehicle classes that could be tested with this system. For each vehicle and application class, this technology could be used to develop new duty cycles that are each characteristic of a specific class of vehicles and its associated uses, with different cycles developed for urban, rural, and long-haul-type applications.

Vehicle load patterns also change with the time of day. An urban bus driving during morning or afternoon rush hour traffic will rarely, if ever, experience traffic patterns such as those simulated in a CBD or New York City Bus cycle. Real world traffic is much more congested than what these cycles depict, thus stops and starts are much more frequent. Even freeway traffic, as seen in Figure 6-13, does not flow as smoothly as the Commuter Phase test cycle simulates. The on-board emissions measuring system could be used to characterize how traffic flow patterns, and consequently emissions profiles, change during the course of a day. Such endeavors could result in substantial improvements in emissions inventory models by removing the discrepancies between simulated test cycles and real world driving.