West Virginia University
Center for Alternative Fuels, Engines & Emissions

REPORT

Correlation between West Virginia University and Engine, Fuel and Emissions Engineering, Inc.'s RAVEM Emissions Measurements from Transit Buses

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Objectives

The primary objective of this report is to compare the emissions data measured by the West Virginia University (WVU) Transportable Heavy Duty Emissions laboratory and the "Ride Along" Vehicle Emissions Measurement (RAVEM) system from Engine, Fuel and Emissions Engineering, Inc. (EE&FE). In support of this objective, additional quality control data and discussion are presented.

Introduction

During a program to evaluate emissions from transit buses Mexico City under contract GDF-SMA-GEF-SC-027-04 for the Mexico City Secretariat of Environment (SMA), a select number of vehicles had their emissions measured using two independent systems.

The RAVEM system used a partial exhaust constant volume sampling (CVS) method, with isokinetic proportional sampling of the exhaust. The emissions measured by the RAVEM system were:

- Oxides of nitrogen (NO_X) - by chemiluminescent analyzer, in real time and integrated samples
- Carbon dioxide (CO_2) - by non-dispersive infrared (NDIR) analyzer, in real time and integrated samples
- Carbon monoxide (CO) - by NDIR analyzer, in real time and integrated samples
- Particulate matter (PM) – integrated sample collection on pre-weighed filters, with weighed filters

The WVU Transportable Laboratory used a full-scale exhaust dilution tunnel as per the United States Code of Federal Regulations, Volume 40, Part 86. A detailed description of the dynamometer and emissions measurement procedures can be found in the literature (1). A partial list of emissions measured by the WVU Transportable Laboratory is presented in Table 1.

Oxides of Nitrogen (NO_X)	Wet Chemiluminescent
Hydrocarbons (HC)	Heated Flame Ionization Detector (HFID)
Carbon Monoxide (CO)	Non-dispersive Infrared Detector (NDIR)
Carbon Dioxide (CO_2)	Non-dispersive Infrared Detector (NDIR)
Particulate Matter (PM)	Fluorocarbon Coated Filter Media (Integrated) Tapered Element Oscillating Member (Continuous)

Table 1 - Emissions Measured by WVU

The integrated emissions collected by WVU were all corrected for background levels. Background correction employed the test dilution factor, as described in Appendix A.

RAVEM Data

RAVEM data were supplied simultaneously to WVU and to Gregory Rideout of Environment Canada. Similarly, WVU supplied data and Mr. Rideout distributed the whole data set to EF&EE and WVU.

Test Vehicles

Table 2 provides information on the vehicles tested in the correlation program.

Ref. Name	Vehicle	Transmission	Test Weight (lbs)	Curb Weight (lbs)	Passenger Capacity	Odometer Reading (miles)	Engine
Allison	2004 Allison	Hybrid	35000	29000	113	36846	2002 Cummins ISB-230
RTP1	2002 Marcopolo	5 Speed Auto	30070	21100	85	100142	2002 Mercedes-Benz OM906LA
RTP3	2002 Marcopolo	5 Speed Auto	30220	21250	85	89333	2002 Mercedes-Benz OM906LA
Scania18	2004 Scania	4 Speed Auto	57025	40075	161	998	2004 Scania DC9-300

Table 2 - Summary of vehicles tested during the correlation program.

WVU Transportable Laboratory Quality Control and Quality Assurance

To ensure measurement accuracy, the WVU laboratories follow a set of QA/QC guidelines. These guidelines include scheduled calibration and maintenance for emissions and dynamometer measurement devices. A more complete discussion of QA/QC procedures is contained Appendix B. After setting up the laboratory in Mexico City, the WVU field engineers performed extensive instrument calibrations, as presented in the US Code of Federal Regulations, Title 40, Part 86, Subpart N (CFR 40), which include

- Methane response (CFR 40 86.1321-94)
- Hydrocarbon analyzer response optimization (CFR 40 86.1321-90)
- O_2 interference checks for hydrocarbon analyzer
- CO analyzer CO_2 and water interference check (CFR 40 86.1322-84)
- NO_X analyzer efficiency checks (CFR 40 86.1323-84)
- CVS system verification (propane injection) (CFR 40 86.1319-90)
- Gaseous and particulate emissions sampling system leak checks
- Calibration of power absorber load cells

Appendix B (Mexico City Test Plan) shows the QA/QC check sheet used by the WVU staff in Mexico City. Specific Quality Control efforts are discussed below.

CVS System Verification

A satisfactory constant volume sampling (CVS) system verification is critical to obtain accurate measurements. The system is verified by introducing a known mass of propane into the tunnel, and measuring its recovery with a hydrocarbon analyzer. While the blower is operating to draw air through the dilution tunnel, a known flow rate of propane is introduced into the tunnel inlet. The propane injection rate is controlled using a Horiba propane injection kit which includes a calibrated orifice, precision pressure gage and gas temperature monitoring thermocouple. The response from the hydrocarbon analyzer is recorded for 300 seconds and the mass of propane injected is compared to that recovered at the sampling plane and measured by the hydrocarbon analyzer. This QA/QC check reveals whether there are any leaks in the dilution tunnel/CVS system and verifies the calibration of the CVS system. As per CFR 40, the difference between the mass of propane injected and the mass of propane recovered must not exceed 2%. Laboratory personnel performed two CVS system verification checks in Mexico City with percent differences of 1.240% and 0.503%. This has a secondary benefit of confirming proper function of the hydrocarbon analyzer.

Analyzer Calibration

Each emission analyzer is calibrated using a NIST standard calibration gas. The analyzer is calibrated when that analyzer's range is changed and periodically as the instrumentation engineer deems necessary. The procedure for calibrating gaseous emissions analyzers involves recording their response to various gas concentrations (0%, 10%, …, 90%, 100% of full scale concentration) and generating a least-squares best-fit polynomial equation to translate the response of the analyzer to the gas concentration. The instrumentation engineer also periodically checks the 0% and 100% analyzer response to account for slight analyzer drift throughout each test day. Figure 1 through Figure 3 show calibration curves for CO_2, CO and NO_X recorded on October 24, 2004.

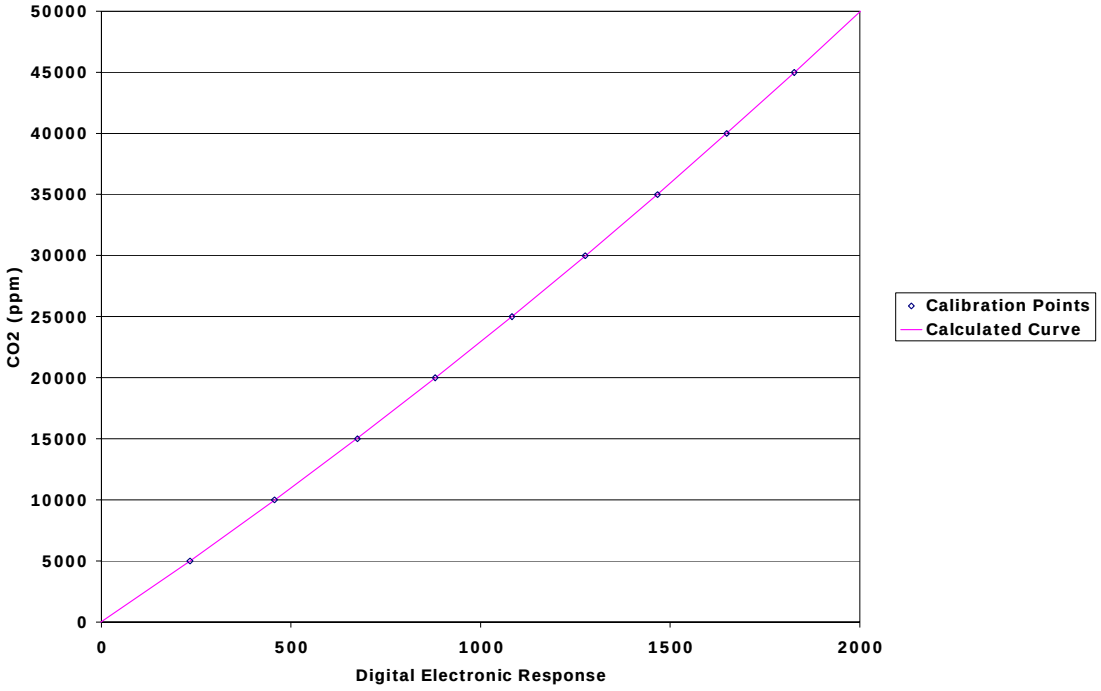

Figure 1- Calibration curve for the carbon dioxide analyzer (October 24, 2004).

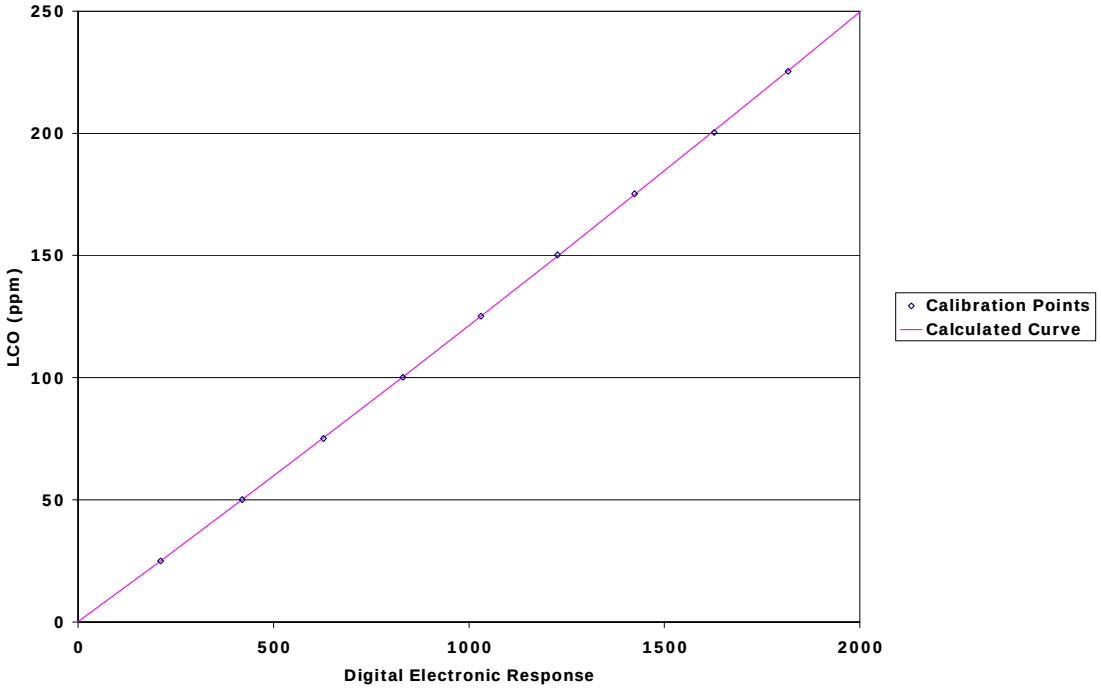

Figure 2 - Calibration curve for the low range carbon monoxide analyzer (October 24, 2004)

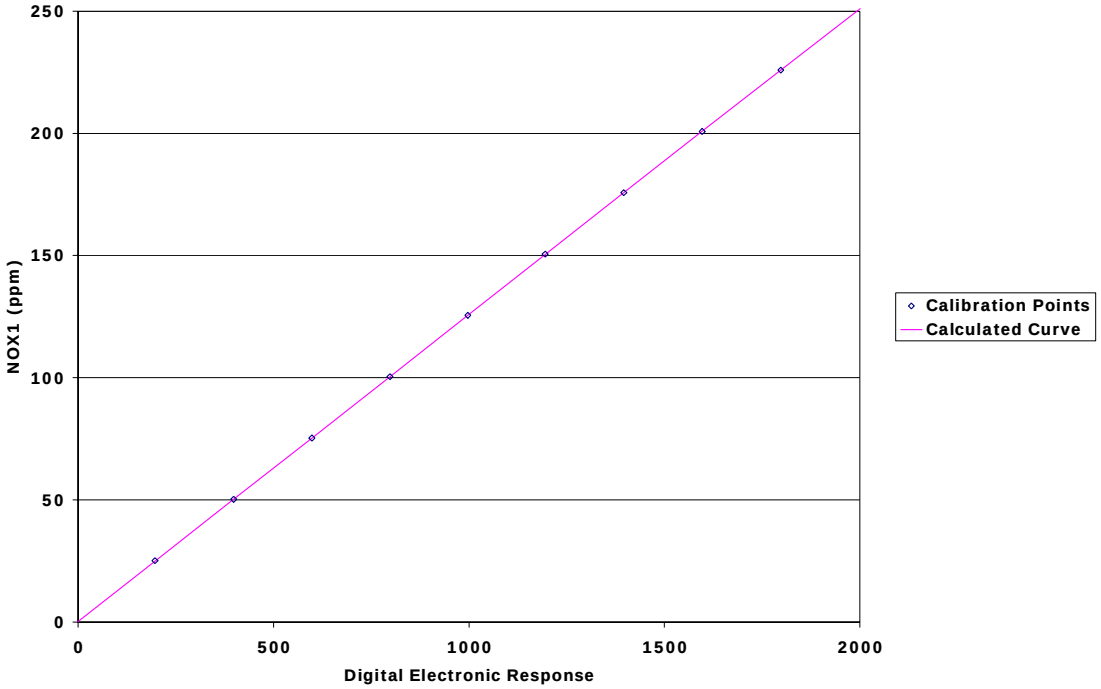

Figure 3 - Calibration curve for the oxides of nitrogen (primary) analyzer (October 24, 2004).

Particulate Matter

In Mexico City, WVU used a second, separate method to measure PM in addition to the conventional 70mm filters. A Tapered Element Oscillating Microbalance was used to sample from the WVU dilution tunnel. The TEOM is an automated, filter-based measuring device manufactured by Rupprecht & Patashnik (East Greenbush, NY). While the TEOM analyzer is not certified as a replacement for filter media, it does provide instant feedback on PM emissions levels. Traditional filter media must be conditioned to a specific temperature and humidity in an environmental chamber prior to weighing.

In Mexico City, the WVU TEOM measured less PM than the WVU filter, but the correlation was good (R^2 = 0.977). The TEOM avoids human weighing errors, and the high correlation between the TEOM and WVU filter data acts as a Quality Control tool for WVU. Figure 4 shows continuous TEOM data recorded during testing of a bus over the European Transient Cycle (ETC) while Figure 5 shows a comparison of particulate measurements found using filter media and the TEOM analyzer.

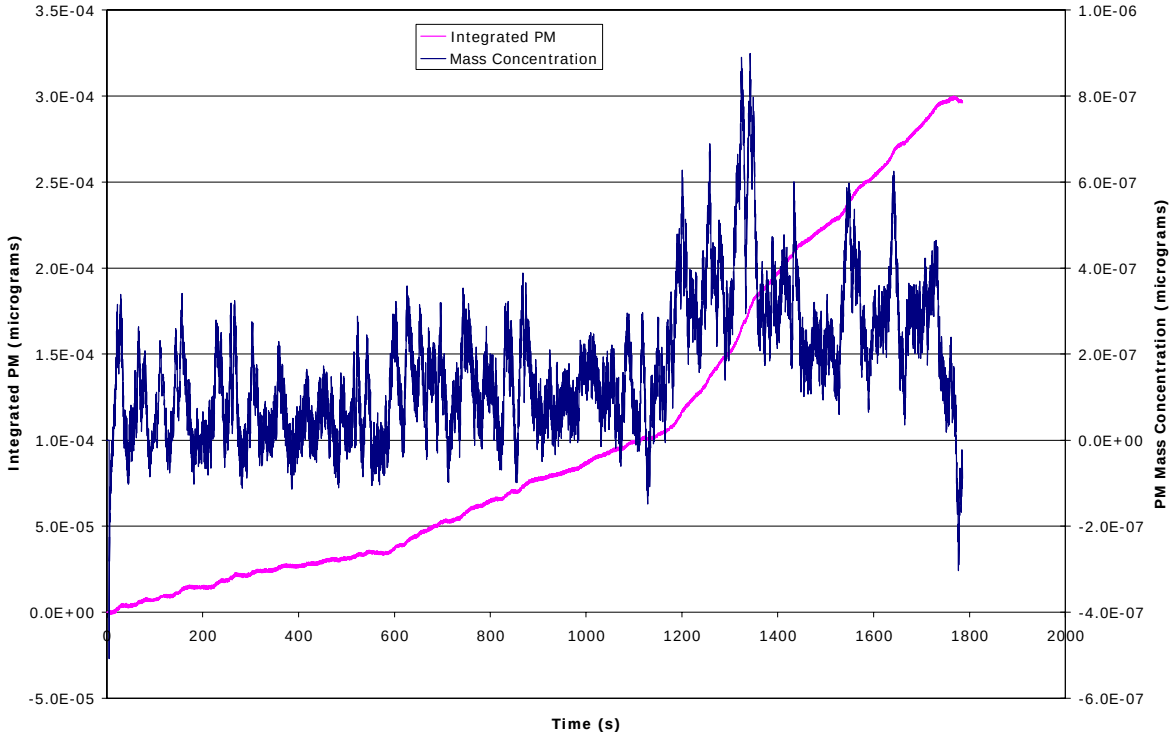

Figure 4 - TEOM Particulate data over the ETC.

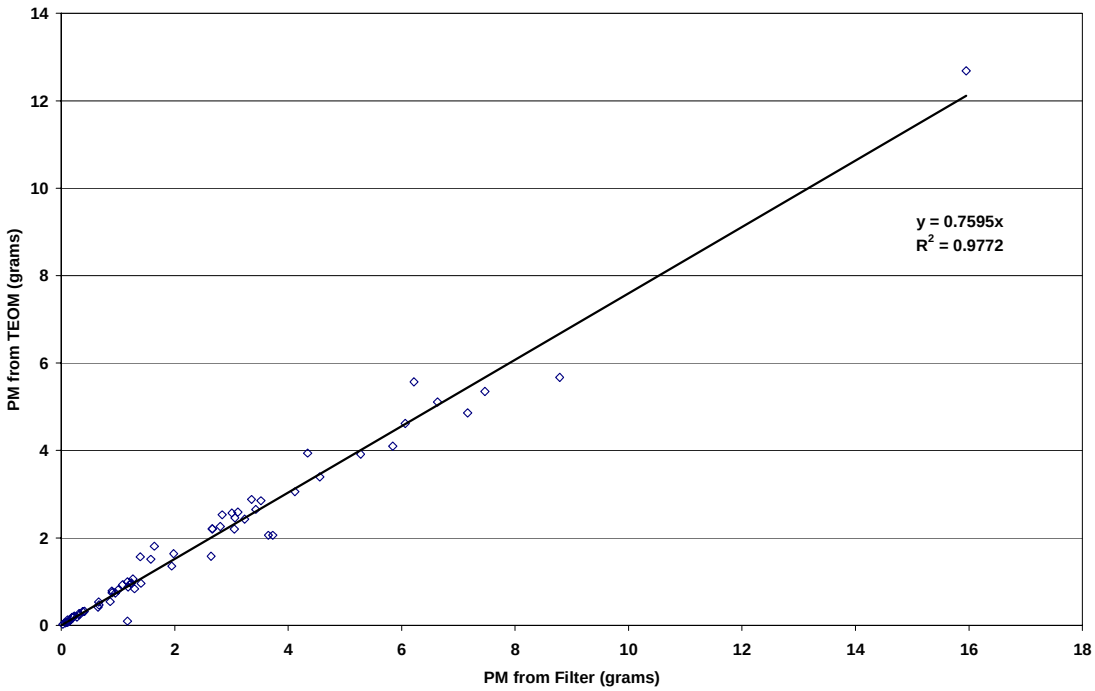

Figure 5 - Comparson of filter and TEOM particulate measurements from Mexico City

An Australian study found that the TEOM reported 16% less mass than a PM filter, on average (1). Gilbert and Clark (2) examined this relationship as the sampling temperature and flow rate of the TEOM were adjusted. Kelly and Morgan (3) found that the TEOM reported 20 to 25% less mass than the filter. Other workers, including Moosmuller et al. (4), have confirmed that the TEOM measures less mass than a filter. It is usually argued that the TEOM may lose more organic carbon (stripped out of the filter) during the measurement process. It is not known how altitude might affect the relationship between filter and TEOM measurements.

As illustrated in Figure 5, the filter and TEOM measurements correlate well with the TEOM reporting at 76% of the filter measurement.

Oxides of Nitrogen

WVU employed two separate analyzers for NO_X, because this is a species of great importance. There was excellent agreement between these two analyzers, as shown in Figure 6. This also confirms that the conversion of NO_2 to NO by the individual analyzers was similar.

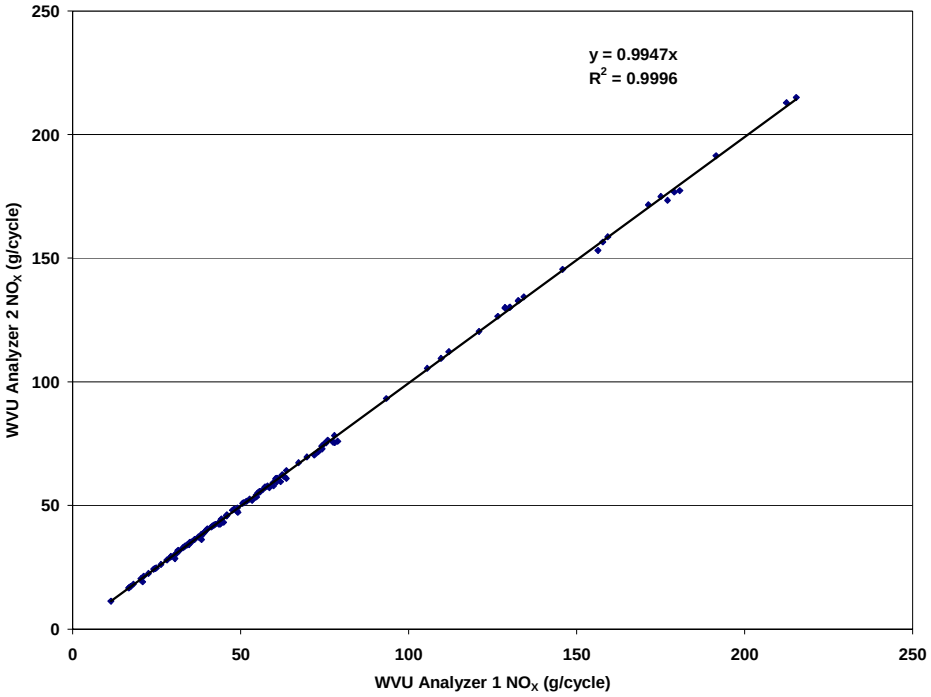

Figure 6 - Correlation of WVU NO_X 1 and NO_X 2 analyzer performance. This includes data for runs outside those considered for the correlation study.

Fuel Usage

The amount of fuel used during an emissions test is calculated using a carbon balance equation with a reasonable assumption of diesel fuel composition (CFR 40 Part 86.1342-90).

Equation 1 - Fuel usage from carbon emissions equation.

$$M_{Fuel} = HC_{Mass} + \frac{[0.429CO_{Mass} + 0.273CO_{2Mass}]}{FFC}$$

Where

HC_{Mass}	= Mass of hydrocarbon emissions
CO_{Mass}	= Mass of carbon monoxide emissions
CO_{2Mass}	= Mass of carbon dioxide emissions
FFC	= Mass percentage of carbon in the fuel

Additional procedures may be used to measure fuel usage. One option is to use an external container as a fuel supply and weigh the reservoir before and after the test. While EF&EE did perform one gravimetric fuel recovery test, WVU participated only in running the vehicle on the dynamometer and was not directly involved in planning or executing the weighing procedure. This test was executed while the vehicle was operated over the Central Business District cycle which is a transient test with 14 “trips” from idle to 20 mph and back to idle, with a total integrated distance traveled of 2 miles. More accurate results could have been obtained by exercising the vehicle through a longer test cycle such that a larger quantity of fuel would be consumed, resulting in more accurate gravimetric analysis. This would also help to minimize the possible effects of fuel from the supply and return lines draining into the measurement container, resulting in an underreporting of fuel consumption. However, EF&EE personnel took care to ensure that the fuel lines to and from the tanks were filled with fuel. Also, a larger quantity of fuel would minimize fuel heating and the possible effect of higher temperature fuel altering the behavior of the engine fuel management system. There was concern from the WVU field engineers over fuel temperature rise during the fuel economy measurement. In retrospect, it would have been desirable to include a carefully planned fuel consumption test in the correlation.

Another option to measure fuel usage is to obtain continuous fuel delivery information from the vehicle on-board electronic control unit. While WVU did not obtain ECU fueling data from any of the vehicles tested in Mexico City, the researchers have been able to do so for a variety of other heavy duty vehicle and engine studies. Figure 7 shows a comparison of fuel usage calculated from emissions data and that reported by the vehicle ECU from tests performed by WVU under other research programs. Each fitted line represents a different vehicle. As can be seen from the least squares fitted regression lines, calculation of fuel usage differs from values reported by the ECU numbers (+12.05%, +2.35%, +5.35%, -4.86%) where a positive percentage represents and overprediction of fuel usage. The uncertainty in the data is on the order of ±5% due to assumed fuel properties used in the calculations as per CFR 40, Part 86.

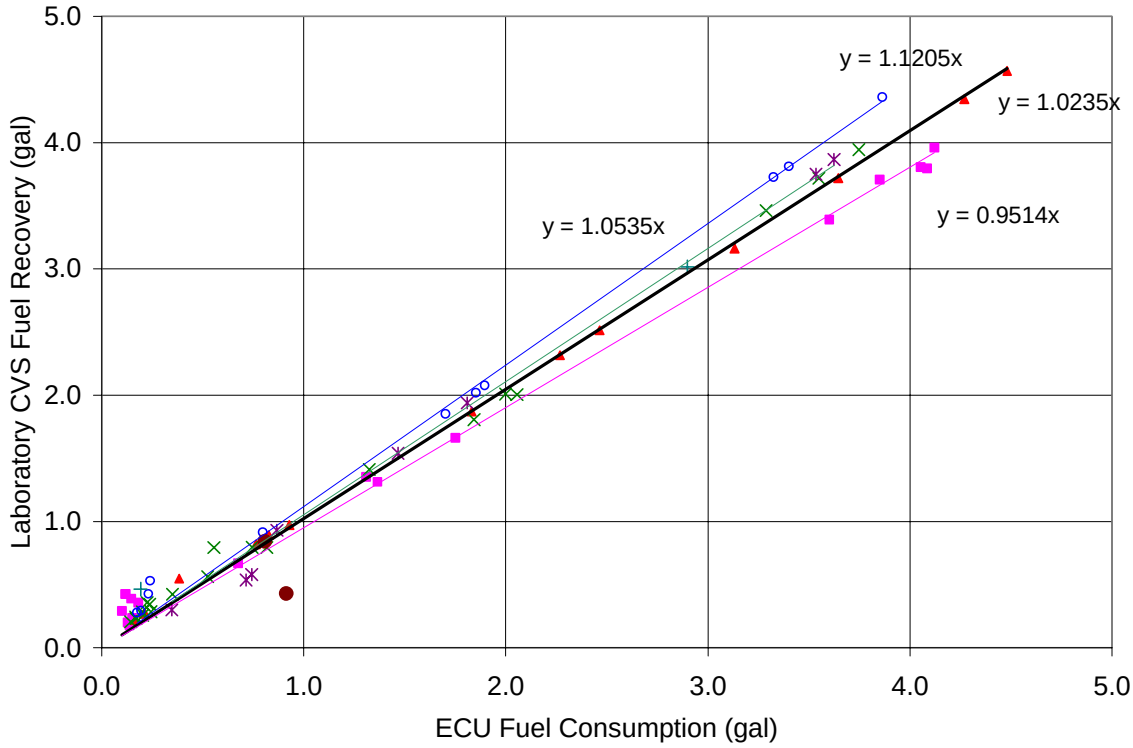

Figure 7 - Comparison of ECU fuel consumption to CVS calculated fuel recovery.

Figure 7 shows that, when compared with an independent measurement, the WVU methodology for determining fuel consumption is reasonably accurate.

Carbon Monoxide

Carbon monoxide emissions are highly correlated with transient vehicle operation with transient emissions concentrations typically 20 to 30 times the concentrations at idle emissions. The periods of high emissions during transients occur over a small percentage of each test while lower level emissions dominate during steady state, deceleration and idle operation. In order to record both the transient spikes and maintain good resolution during non-transient operation, WVU employs two carbon monoxide detectors, one calibrated in a low detection range and the other in a high range. Figure 8 shows recorded carbon monoxide emissions from both the high range (500 ppm) and low range (100 ppm) analyzers while a bus was exercised over the European Transient Cycle in Mexico City. During transient operation, the higher ranged CO analyzer is able to record emissions while the lower ranged analyzer exceeds its measurement capabilities. While the higher ranged analyzer captures every event, the type of analyzers used (NDIR) for both high and low range CO measurement are less accurate in the lower ten percent of their range and the reported CO is obtained from analysis of the integrated bag sample using the lower ranged analyzer.

	Averaged Continuous (ppm)	Integrated Bag (ppm)
High Range CO	15.63	22.14
Low Range CO	22.86	30.81

Table 3 - Integrated carbon monoxide data from the Scania 18 bus over the ETC.

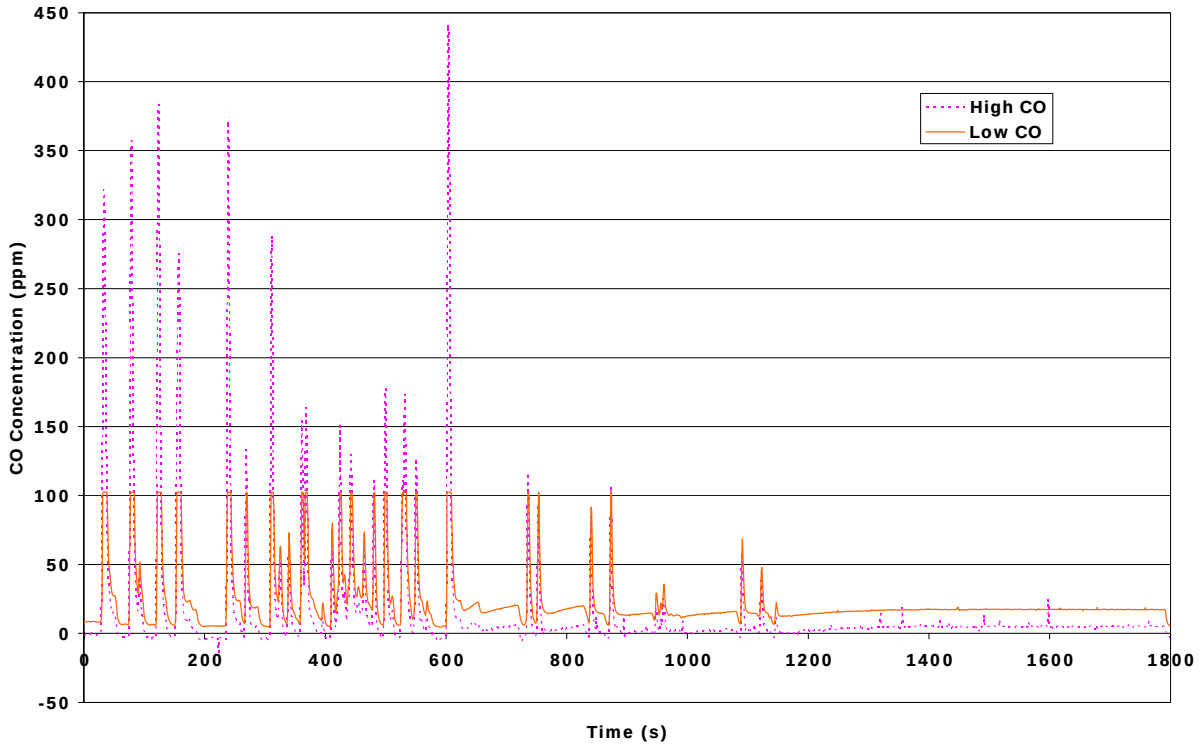

Figure 8 - Carbon monoxide emissions from the Scania 18 bus over the ETC.

DESCRIPTION OF THE RAVEM SYSTEM

The RAVEM emission measurements were performed using Ride-Along Vehicle Emission Measurement (RAVEM) system serial number 002, belonging to the Secretaría de Medio Ambiente (SMA) of the Government of Mexico City.

The RAVEM is one of a new class of portable emission measurement systems that have begun to become available in the last few years. The RAVEM technology was developed by Engine, Fuel, and Emissions Engineering, Inc. (EF&EE).

The SMA system was the second RAVEM system to be produced, and the first to be sold commercially. At the time that this project started, the SMA RAVEM system had only recently been delivered, and was still in the processing of being set up and validated. As might be expected for the first use of such a complex system, there were a number of start-up problems to be overcome, and which affected the testing to a greater or lesser degree.

PRINCIPLES OF OPERATION

The RAVEM system is described in two published papers (6, 7), so its operating principles are summarized only briefly here. The RAVEM system is based on proportional *partial-flow* constant volume sampling (CVS) from the vehicle exhaust pipe. The CVS principle is widely used for vehicle emission measurements because the dilution arrangements are such that the pollutant *concentration* in the CVS dilution tunnel is proportional to the pollutant *mass flow rate* in the vehicle exhaust. Pollutant concentrations can be measured readily, while exhaust mass flow rates are difficult and expensive to measure accurately, especially under transient conditions, as when driving on the road.

The total pollutant mass emissions over a given driving cycle are equal to the integral of the pollutant mass flow rate over that cycle. In a CVS system, this integrated value can readily be determined by integrating the concentration measurement alone; the CVS mass flow rate enters only as a constant multiplier. This integration can be accomplished either numerically or physically. The exhaust mass flow rate does not enter directly into the calculation, making it unnecessary to measure. A schematic diagram of the RAVEM system is shown in Figure 9. Except for the isokinetic sampling system at the top of the figure, this diagram closely resembles a conventional single-dilution CVS emission measurement system.

For gases, the RAVEM system uses both numerical and physical integration. Concentrations of NO_X, CO_2, and CO in the dilute exhaust gas are recorded second-by-second during each test. In addition, integrated samples of the dilute exhaust mixture and dilution air are collected in Tedlar® bags during the test, and analyzed afterward for NO_X, CO_2, CO and (optionally) other pollutants.

In CVS sampling for particulate matter, sample integration is accomplished physically, by passing dilute exhaust mixture through a pre-weighed filter at a constant, controlled flow rate. The weight gain by the filter is then divided by the volume of mixture passed through it to yield the average particulate concentration over the test cycle.

Conventional emission laboratory methods defined by the U.S. EPA (8) and California ARB utilize full-flow CVS, in which the entire exhaust flow is extracted and diluted. The resulting air-handling requirements make full-flow CVS impractical for portable systems, however. The design of the RAVEM system surmounts this obstacle by extracting and diluting only a fraction of the total exhaust flow, using a patented isokinetic proportional sampling system. Since the RAVEM's sampling system takes only a small fraction of the total exhaust flow, the dilution air requirements and dilution tunnel size can be reduced to levels compatible with portable operation.

Pollutant concentration measurements in the RAVEM system follow the methods specified by the U.S. EPA and ISO standard 8178. The pollutants measured during the correlation program were as follows:

- Oxides of Nitrogen (NO_X) by chemilumenescent analysis of the dilute exhaust sample,
- Carbon monoxide (CO) and carbon dioxide (CO_2) by non-dispersive infrared analysis of the dehumidified dilute exhaust sample;
- Particulate matter (PM) by collection particulate matter on pre-weighed filters of Teflon-coated borosilicate glass fiber, followed by post-conditioning and reweighing of the exposed filters.

The capabilities of measuring aldehydes (by HPLC analysis of DNPH cartridges) and volatile organic compounds (by GC analysis) were subsequently added to the RAVEM system, and were not employed in this test program.

RAVEM SYSTEMS AND OPERATION

The RAVEM system comprises the following key subsystems.

- Constant volume dilution system
- Isokinetic sampling system
- Bag sampling system
- Gas analyzer system
- Particulate sampling system
- Cartridge sampling system

- Data processing and handling system
- Auxiliary inputs

Each of these is briefly discussed below.

Constant-Volume Dilution System

This constitutes the heart of the RAVEM system. As diagrammed in Figure 9, the variable speed blower draws dilute air/exhaust gas mixture out of the dilution tunnel at a constant rate (expressed in standard liters per minute). Raw exhaust gas enters the dilution tunnel near the upper end, where it mixes with filtered dilution air. The relative proportions of exhaust gas and dilution air are controlled by the isokinetic sampling system.

The venturi, temperature, and pressure sensors between the dilution tunnel and the blower supply the feedback data to maintain this constant flow. This system is calibrated against a highly-accurate thermal mass flow meter (not shown) in order to compensate for any drift. High accuracy is needed, as any error in the mass flow will result in a proportional error in the final results.

Following the completion of this test program, a small leak was found in the connection between the CVS blower and the thermal mass flow meter, due to a hole provided for a setscrew. This leak allowed 7 percent of the air/exhaust mixture passing through the dilution tunnel to bypass the thermal mass flow meter. This affected the system calibration, resulting in CVS flow values that were 7% too low. Results of CO_2 recovery tests taken before and after this correlation test program confirm that this error was present during the test program. This error was included in the data initially reported, but has been corrected in the data presented in this report.

Isokinetic Sampling System

The isokinetic sampling system comprises the sampling probe in the exhaust pipe, an insulated sample line connecting the probe to the raw gas inlet on the dilution tunnel, and the system for controlling the sample flow to maintain isokinetic conditions. The control system uses static pressure taps on the inside and outside surfaces of the probe, connected to a sensitive differential pressure gage. When this gage reads zero, the inside and outside pressures are the same. This requires that the velocities inside and outside the sample probe also be equal – i.e. isokinetic. The throttle at the upstream end of the dilution tunnel varies the pressure in the dilution tunnel as needed to bring about this condition. The fan upstream of the throttle extends the possible range of dilution tunnel pressures to include slightly positive as well as negative values (compared to ambient atmospheric pressure).

Since the control system depends on equalizing the static pressures measured inside and outside the probe, any leaks or other problems in the pressure taps, pressure lines, or differential pressure sensor that affect the measured pressure difference will result in under- or over-sampling of the exhaust. Two isokinetic probes were used during this test program: one (identified as probe Mx01) that had been manufactured for and supplied with the RAVEM system, and a second (identified as the EF&EE probe) that had been manufactured earlier and previously used in the EF&EE RAVEM system. Probe Mx01 was subsequently found to give inconsistent results, due to what is believed to be a leak in one of the differential pressure lines.

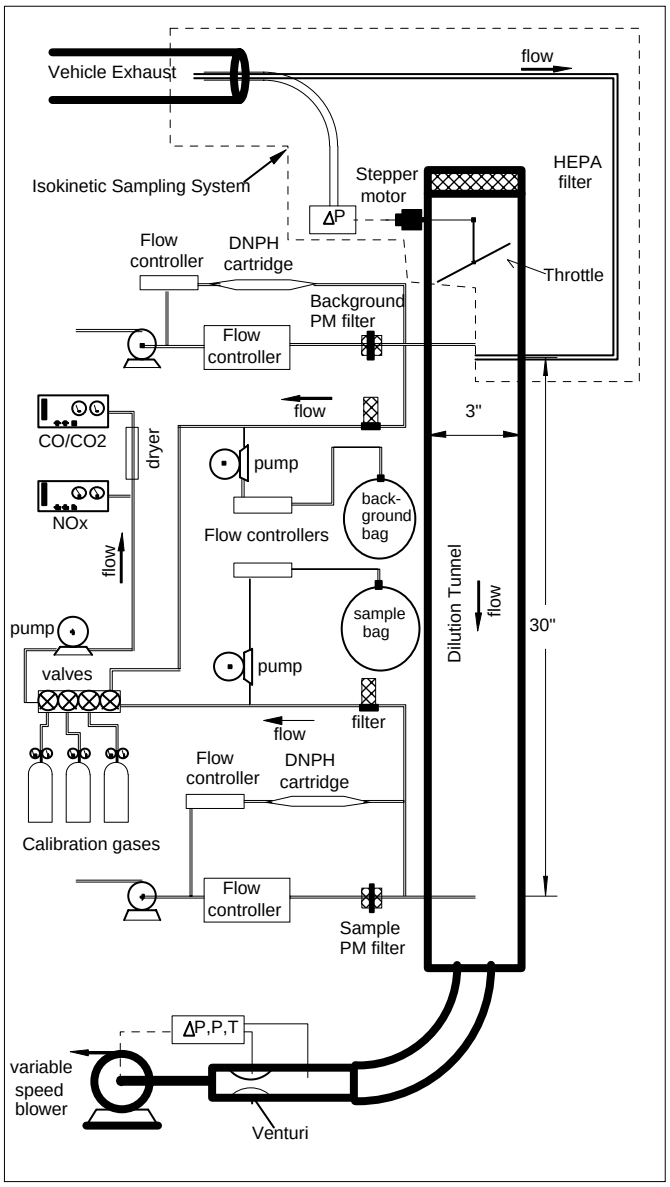

Figure 9: Schematic diagram of the RAVEM system

The effect of any leaks in the differential pressure lines would have been different (and probably greater) during the correlation tests with the WVU system than in normal on-road emission measurements. Normally, the RAVEM's isokinetic sampling probe is inserted in the end of the exhaust system where it discharges to atmosphere. For this test program, however, the probe was installed in the exhaust system upstream from the WVU's full-flow CVS. The pressure losses in the downstream piping resulted in the RAVEM probe being placed at higher-than-atmospheric pressure over most of the driving cycle. Combined with the pressure leak in the Mx01 probe, this caused the isokinetic sampling system to over-sample the exhaust. In normal field use, this same condition resulted in under-sampling, especially at idle.

Bag Sampling System

The bag sampling system is designed to fill one pair of Tedlar bags for each test. One bag contains an integrated sample of the dilute exhaust from the dilution tunnel, and the other contains an integrated sample of the dilution air. Two choices are available with respect to the Tedlar bags: a pair of internal bags having a usable volume of about 10 liters, or a pair of 60 liter external bags fed through two quick-connect ports on the exterior of the system unit. The system is designed to allow the external bags to be exchanged quickly between tests, so that the bag samples for each test can analyzed off-board – e.g. by gas chromatograph. A pair of manually operated three-way valves selects the internal or external bags.

For each bag, gas is drawn from a sample port in the dilution tunnel, through a filter to a small pump. It then passes through a mass flow controller to the bag selector valve, and thence to the bag. Any leaks in the sample bag will directly affect the bag emission results. A leak check is therefore performed in the process of emptying the sample bags before each test.

Gas Analyzer System

The gas analyzer system comprises a sample pump, valve manifold, and conventional laboratory-grade heated NOx and ambient-temperature CO/CO_2 analyzers installed in a shock-mounted 19 inch rack inside a protective case. The NO_X analyzer is a California Analytical Instruments HCLD 400 equipped with an NO to NO_2 converter using activated carbon. The analyzer is maintained at 60^{o}C, making it unnecessary to dry the sample to avoid condensation. Dry, low-pressure compressed air for the ozone generator is supplied by an on-board pump by way of a filter and desiccant cartridge.

The CO/CO_2 analyzer is a California Analytical Instruments model ZRH using non-dispersive infrared (NDIR) analysis. Water vapor interferes with the NDIR measurement, especially for CO, and must be removed from the sample. This is accomplished by passing it through a Nafion™ semi-permeable membrane mass-exchanger. Dry gas for the other side of the mass exchanger is supplied by a small pump circulating air through a desiccant cartridge.

The valve manifold allows the analyzer sample feed to be drawn from any one of the following sources: the dilute exhaust mixture in the dilution tunnel, the dilution air entering the tunnel (for background measurements), the integrated sample bag, the integrated background bag, zero gas, CO/CO_2 span gas, or NO_X span gas. The latter three gases are used for calibration, and are supplied to quick-connect ports on the exterior of the RAVEM system unit. During an emission test, gas concentrations in the dilute exhaust are monitored continuously, and recorded about once per second. After the test ends, the analyzers are normally calibrated, and then used to read the concentrations in the sample and background bags.

Since the second-by-second pollutant readings can be affected by drift, vibration, and changes in background pollutant concentrations as the vehicle drives, the bag data are normally more accurate, and are generally the ones reported. The second-by-second data are useful for examining the variation in emissions over the driving cycle, and also provide a backup should the bag results be compromised – e.g. by bag failure during a test. Several of the earlier tests in this program were affected by a suspected leak in the sample bag, so that the integrated second-by-second data were reported instead of the bag data.

Particulate Sampling System

The particulate sampling system comprises a vacuum pump, two flow controllers, two shutoff valves, and two filter holders: one for the PM sample, and one for the background dilution air. Each filter holder contains two 37 mm filters in series. The filters are composed of Teflon-coated borosilicate glass, and meet U.S. EPA and ISO 8178 specifications for diesel PM measurement. At least two sets of filter holders are used, and they are designed to be quickly connected and removed from the sampling system – thus allowing one emission tests to go on while the filters from the last test are being exchanged for the filters for the next.

During an emission test, the shutoff valves are opened, and the dilute exhaust gas and dilution are drawn through their respective filter sets. The filtered gas then passes through the flow controllers to the vacuum pump, where it is exhausted. The filter set exposed to the dilution air provides a "blank" sample for each test, correcting for the effects of changing humidity, atmospheric pressures, and any ambient PM (including condensable species) present in the filtered dilution air. Experience has shown that such corrections can amount to 0.01 to 0.02 g/BHP-hr, which is of the same order as the measured PM emissions for the DPF-equipped vehicles in this study.

Cartridge Sampling System

The cartridge sampling system was not present during the emission testing campaigns reported here. This description is provided only for completeness, and because consideration is being given to including cartridge sampling for carbonyls in the final test campaign.

The cartridge sampling system is similar in design to the PM sampling system described above, comprising two shutoff valves, two holders for SKC 6 mm glass sampling tubes, two flow controllers, and a single pump. It differs from the PM system in having much lower designed flow rates (i.e. 0 to 2 liters per minute, rather than 0 to 30), and in drawing from the filtered sample stream that also feeds the Tedlar bags, rather than directly from the dilution tunnel.

To measure the concentration of carbonyls such as formaldehyde, acetaldehyde, and acetone, the cartridge sampler is loaded with two 6 mm glass tubes containing DNPH-impregnated silica gel. Gas is drawn from the sample and dilution air ports, through filters, and then through the cartridges, where any carbonyls present react with the DNPH and are retained in the cartridge. The cartridges are then removed, placed in a cooler at approximately 4 ^{o}C, and transported to the laboratory, where they are kept in a freezer until analysis by HPLC.

Data Processing and Handling System

The data processing and handling system comprises a laptop computer, connected to a National Instruments Fieldpoint system containing 24 analog-to-digital channels, 8 digital-to-analog channels, 36 digital outputs, 8 general-purpose digital inputs, and 4 counter inputs. These include a number of spare inputs and outputs beyond those required by the RAVEM system itself, making it easy to interface auxiliary sensors.

The RAVEM system measures and records numerous data on a second-by-second basis during each emission test, including the raw inputs and calculated concentrations of CO, CO_2, and NOx, the CVS flow rate, throttle position, and differential pressure gage reading. Calibration data relating the raw inputs and calculated concentrations are also recorded, making it possible to recalculate the second-by-second results using the calibration at the

end of the test. Exhaust temperature and up to two auxiliary temperatures are recorded second-by-second; in addition, the temperature, barometric pressure, and humidity are recorded at the beginning of each test. All of these are stored in separate data file for each test, in a compact binary format.

A data file reading utility is supplied with the RAVEM system. This utility can be used to review and correct the data collected for each test, and to add data developed later such as the post-test weights of the particulate filters. This utility can also copy the data to a Microsoft Excel worksheet file. This file is formatted to be "human readable", and occupies much more space than the compact binary format. Copies of the Excel worksheets for each emission test are given in the CD ROM that accompanies this report, along with summary worksheets that combine the individual test results.

Quality Assurance Measures and Results

RAVEM operating procedures include a number of quality assurance measures. Two key QA procedures are CO_2 recovery tests and fuel consumption checks. The CO_2 recovery check injects CO_2 gas from a cylinder into the dilution tunnel, and compares the CO_2 mass measured to the change in weight of the CO_2 cylinder. This confirms the accuracy of the CVS flow measurement, as well as the gas sampling system and the CO_2 analyzer. As mentioned earlier, CO_2 recovery checks performed prior to the correlation testing with WVU showed a discrepancy of 6 to 8%. The source of this discrepancy was subsequently determined to be leakage through a setscrew hole. Once this hole was plugged, CO_2 recovery checks have shown close agreement between the CO_2 emissions as measured by the RAVEM system and by the change in weight of the gas cylinder.

Fuel consumption checks compare the mass of fuel consumed by the vehicle under test to the fuel consumption calculated from the CO_2 and CO emissions by carbon balance. In addition to the CVS and gas sampling system, this procedure also checks that the isokinetic sampling system is working properly. Table 4 summarizes fuel recovery tests conducted before, during, and after the correlation program with WVU.

Table 4 - Fuel Recovery Test Results for the RAVEM

Test File	Test Date/Time	Vehicle	Test Cycle	Calc Fuel	Weighed Fuel	Calc/ Weighed
MX0017	10/30/04 12:55	RTP 23-955*	Modulo 23	1,161	1,317	88.1%
MX0023	10/31/04 19:17	RTP 23-955*	Módulo 23	965	1,305	74.0%
MX0081	11/12/04 21:23	RTP 23-955**	CBD	914	905	101.0%
MX0193	1/7/05 12:34	RTP 23-0992+	Modulo 23 wo Idle	941	1,040	90.5%
MX0194	1/7/05 13:04	RTP 23-0992+	Continuous Idle	1,014	980	103.5%
MX0203	1/10/05 9:35	RTP 23-1003	Insurgentes Norte	7,871	8,196	96.0%
MX0282	2/3/05 2:42	Busscar GNC	Insurgentes Corredor	6,932	6,750	102.7%
MX0288	2/4/05 4:06	FAW GNC Bus	Insurgentes Corredor	10,353	10,000	103.5%
MX0289	2/4/05 5:36	FAW GNC Bus	Insurgentes Corredor	9,229	8,800	104.9%

* Test with defective probe MX01
** Correlation test with WVU
+ Possibly affected by fuel system leak

Data and Results

Table 5 presents the WVU and RAVEM data used for comparative purposes. The test schedules used were the European Transient Cycle (ETC) and Mexico City Schedule (MCS) except that for one comparison the MX1 mode of the MCS was used alone. There was also one run using the Central Business District (CBD) cycle. Figure 11 through Figure 13 show correlation between emissions (in units of total mass from the whole schedule) from the WVU and RAVEM systems and Figure 14 through Figure 16 show CO_2 corrected emissions, i.e., the ratio of each species to the CO_2 emissions. Except for CO (where there appears to be a constant offset between the two sets of measurements), all correlation plots were constrained to pass through the origin.

Tests MX0038 through Mx0048 in this test program were conducted using the Mx01 isokinetic probe. As mentioned earlier, this probe was subsequently found to give inaccurate results, due to what is believed to be a pressure leak affecting the differential pressure line. This caused the isokinetic sampling system to oversample under most operating conditions, but to undersample at idle. This sampling error directly affected the total mass emission measurements, but did not affect the ratio of one pollutant to another (since all pollutants were equally over- or under- sampled). For this reason, the Mx01 probe data are shown separately in Figure 11 through Figure 13, and are excluded from the correlations, but are included in the correlations in Figure 14 through Figure 16.

As an independent check on system accuracy, EF&EE measured mass fuel consumption directly in one test using the CBD cycle. This measurement was done by weighing a removable fuel tank before and after the test run. Care was taken before the test to ensure that the fuel lines to and from the tank were filled with fuel. Based on these weight measurements, the fuel mass consumed during the CBD test was 905 grams. Assuming a typical diesel fuel composition of $CH_{1.85}$, the CO_2 emissions corresponding to this fuel consumption would have been 2,875 grams. This is agrees closely with the mass CO_2 emissions measured by the RAVEM system (2,907 grams), but is 20% less than the 3,620 grams of CO_2 measured by the WVU system during the same test. This result is shown as the pink square in the plot in Figure 10.

Test ID			Test	PM (g/test)		CO_2 g/test		NOx g/test		CO g/test	
WVU	RAVEM	Vehicle	Cycle	WVU	RAVEM	WVU	RAVEM	WVU	RAVEM	WVU	RAVEM
4339-1	MX0038	Allison	ETC	1.95	0.87	26,847	23,756	120.93	111.0	18.76	-0.4
4341-1 to 3	MX0040	Allison	MCS	0.86	0.95	23,770	20,337	126.50	110.9	18.50	-2.1
4342-1 to 3	MX0041	Allison	MCS	0.29	0.82	23,908	20,780	128.36	110.8	17.44	0.2
4346-1	MX0042	Allison	ETC	0.41	0.41	27,291	28,254	130.14	133.6	9.70	-0.1
4347-1 to 3	MX0043	Allison	MCS	0.46	0.90	23,763	21,632	128.73	119.7	14.67	2.0
4348-1	MX0044	Allison	ETC	0.38	0.49	26,191	27,681	123.00	122.8	7.20	0.0
4349-1 to 3	MX0045	Allison	MCS	0.30	0.93	23,639	20,748	123.56	107.5	12.73	0.0
4353-1 to 3	MX0047	MB #12-592	MCS	4.43	2.97	16,425	14,726	132.55	103.4	74.54	25.2
4354-1	MX0048	MB #12-592	ETC	7.47	3.62	22,527	21,708	159.27	154.1	51.81	25.4
4360-1	MX0058	MB #12-592	ETC	5.84	3.68	23,100	19,885	171.34	163.8	52.71	24.5
4361-1	MX0059	MB #12-592	ETC	4.56	3.25	22,317	19,984	154.32	144.0	47.47	20.0
4362-1 to 3	MX0061	MB #12-592	MCS	4.81	2.83	16,138	10,764	128.67	96.7	81.16	43.8
4363-1 to 3	MX0062	MB #12-592	MCS	4.45	2.34	15,780	11,718	126.78	96.1	75.48	12.3
4364-1 to 3	MX0063	MB #12-592	MCS	3.93	2.63	16,258	12,764	132.71	97.6	67.89	20.3
4365-1 to 3	MX0064	MB #12-592	MCS	3.91	2.47	15,168	11,737	124.56	94.5	65.23	13.3
4399-1	MX0073	Allison	ETC	0.65	1.93	22,419	20,288	111.95	101.7	13.79	-0.1
4400-1 to 3	MX0074	Allison	MCS	0.47	1.00	19,098	15,099	105.51	80.3	24.04	0.0
4401-1	MX0075	Allison	ETC	0.19	0.63	19,519	17,419	91.47	81.5	10.84	-1.3
4407-1	MX0078	MB #23-955	MX-1	#N/A	0.33	3,579	2,480	26.26	17.9	3.50	-1.0
4408-1 to 3	MX0079	MB #23-955	MCS	1.24	0.25	15,363	11,166	110.75	83.4	11.16	0.0
4409-1	MX0080	MB #23-955	ETC	3.65	0.55	19,735	17,842	120.04	110.5	9.16	-4.1
4412-1	MX0081	MB #23-955	CBD	#N/A	0.44	3,620	2,907	24.84	20.3	2.48	-1.4
4418-1 to 3	MX0084	Scania 18m	MCS	8.75	4.80	22,679	18,703	175.06	143.9	97.19	28.3
4419-1 to 3	MX0085	Scania 18m	MCS	8.31	4.74	23,445	19,056	177.02	146.4	99.36	44.8
4421-1 to 3	MX0087	Scania 18m	MCS	10.16	5.39	22,938	18,424	157.77	133.9	110.54	47.8
4422-1 to 3	MX0088	Scania 18m	MCS	9.65	5.97	23,371	18,709	156.33	137.2	104.24	43.8

Table 5 - Data from correlation tests. WVU NO_X data are from the first, or "NO_X1" analyzer.

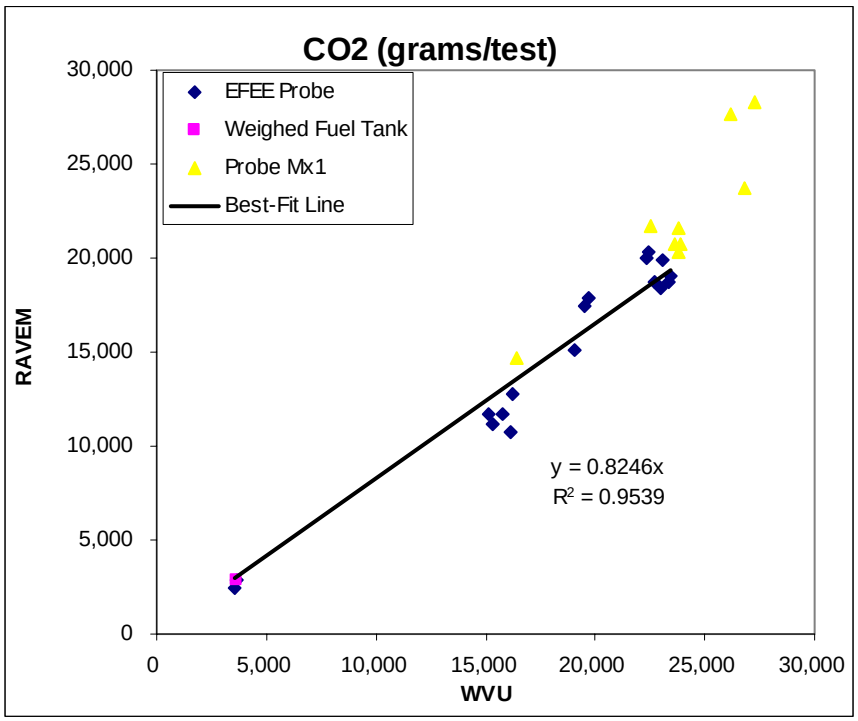

Figure 10 - Correlation of carbon dioxide emissions

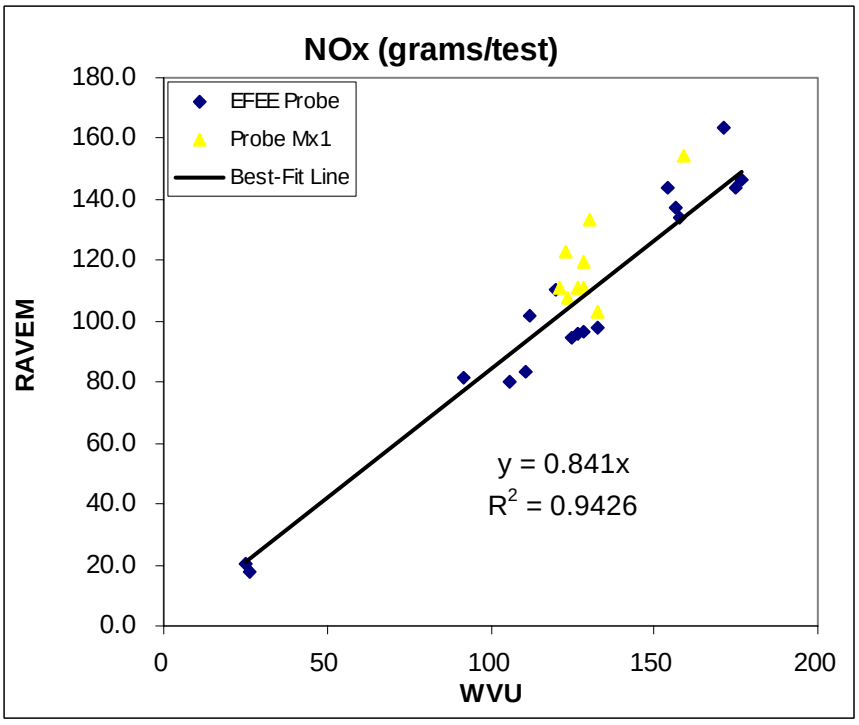

Figure 11 - Correlation of oxides of nitrogen

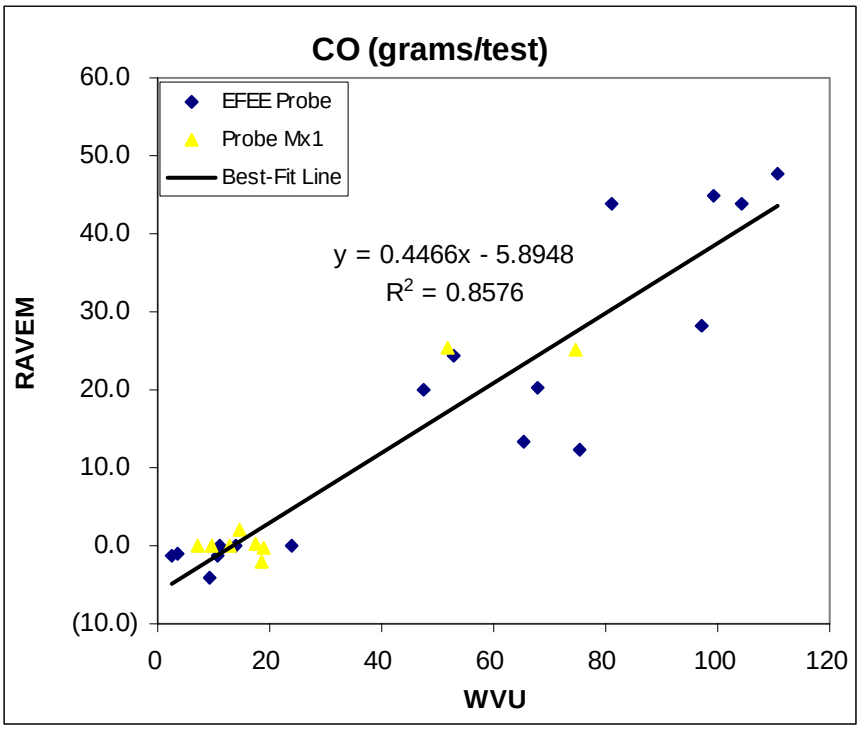

Figure 12 - Correlation of carbon monoxide data.

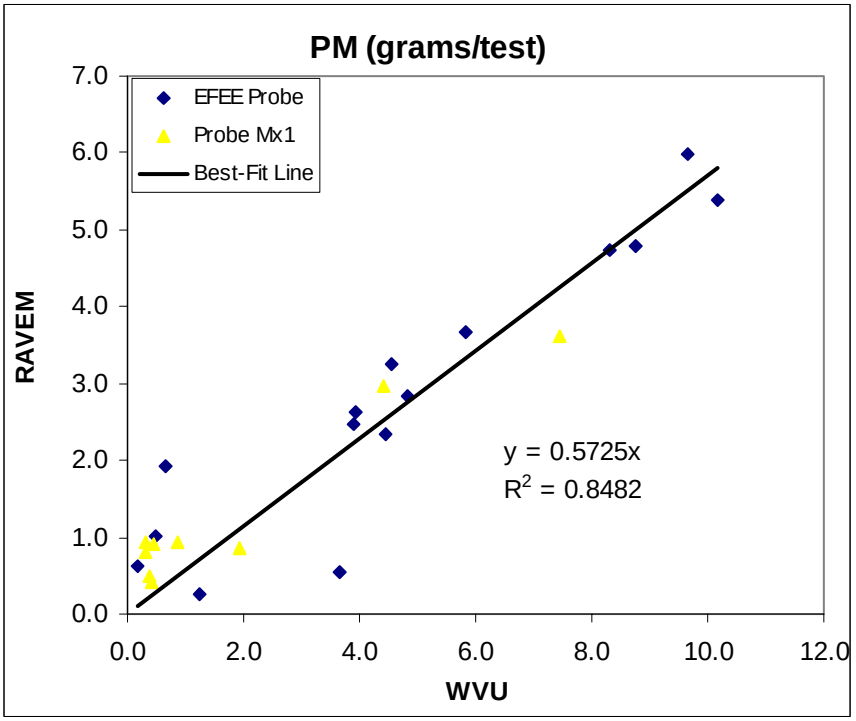

Figure 13 - Correlation of particulate matter emissions.

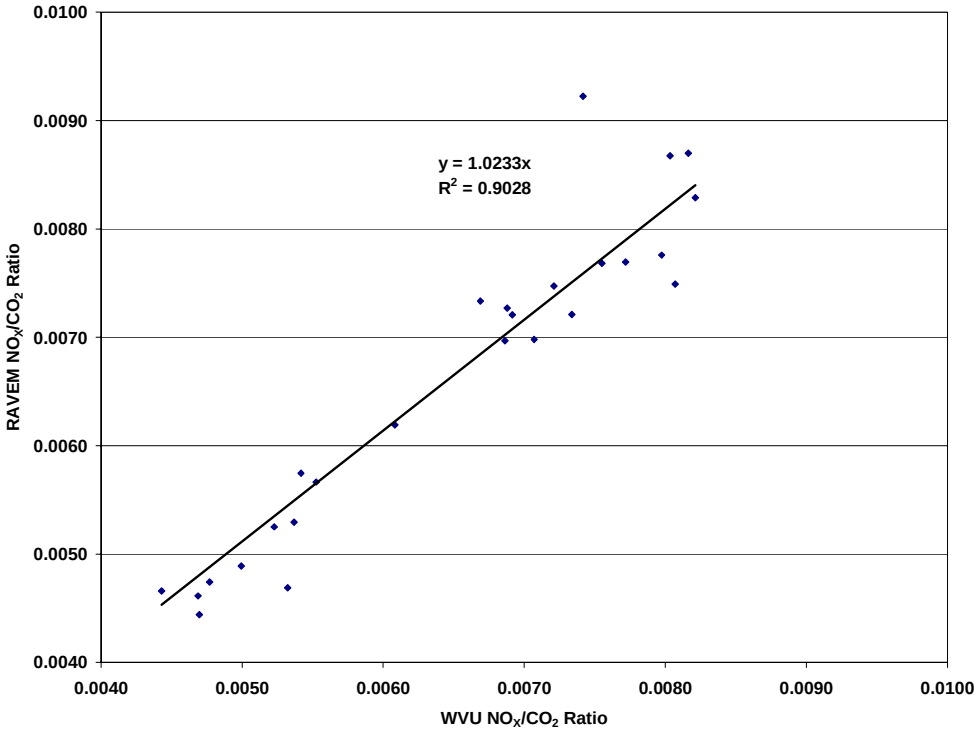

Figure 14 - Comparison of NO_X/CO_2 ratios.

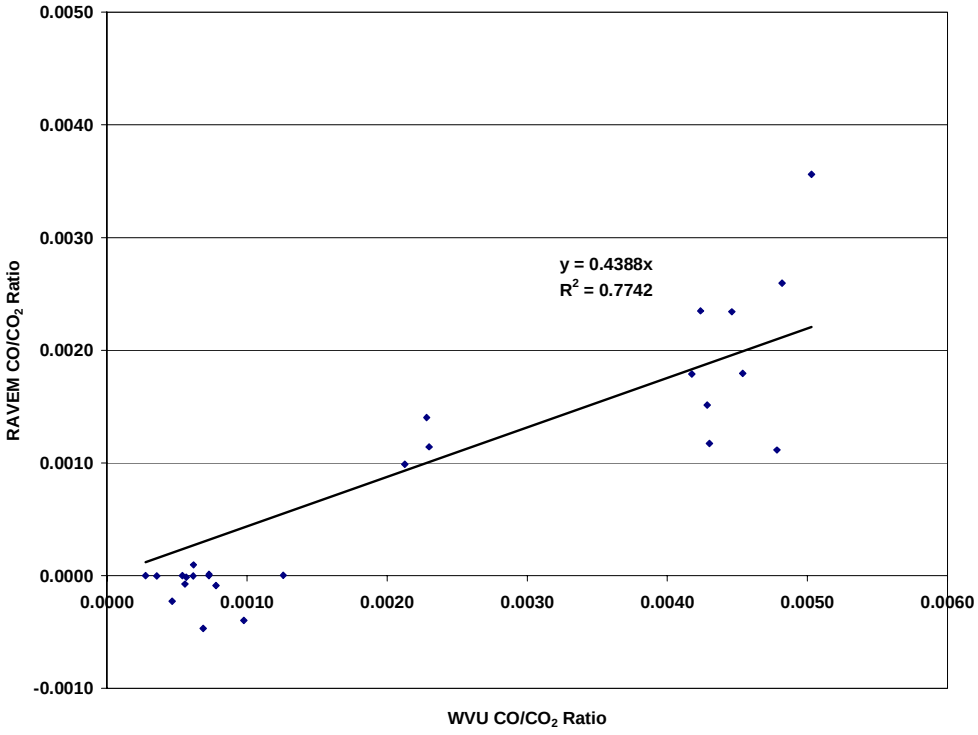

Figure 15 - Comparison of CO/CO_2 ratios.

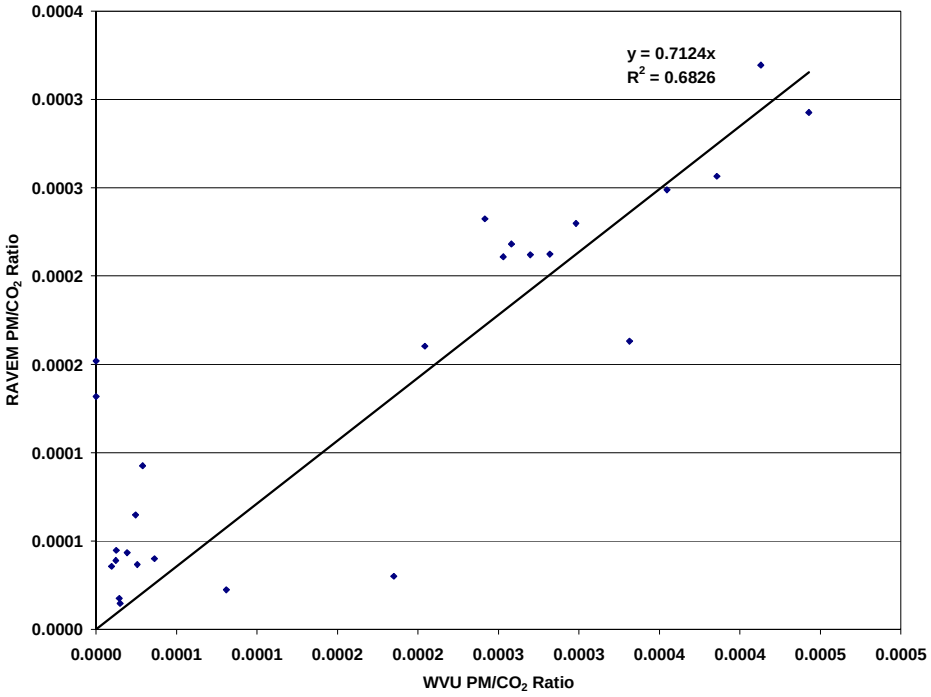

Figure 16 - Comparison of PM/CO_2 ratios.

CO_2 Measurement at Idle

An examination of continuous data from the WVU and RAVEM systems revealed that the RAVEM system was not accurately sampling emissions while the vehicle was idling. This inaccuracy is highlighted in Figure 17. WVU researchers performed a least squares regression analysis of the CO_2 from this individual test (Figure 19) to determine if the differences at idle were the only source of the difference in the integrated results. For this particular test, the data show that the RAVEM reported zero CO_2 flow when the WVU CO2 flow was approximately 0.9 g/sec. In addition, the WVU CO_2 flow was higher than the RAVEM flow, on average, through the whole operating range. Note: the "lag" between the WVU and RAVEM CO2 measurements is a result of differences in sample line residence time between the two systems.

Although the RAVEM system was clearly under-sampling at idle during at least some of the WVU correlation tests, similar undersampling was not observed during on-road emission measurements taken during the same period (compare Figure 17 and Figure 18). This suggests that the undersampling may have been due to some aspect of the RAVEM installation during the WVU correlation tests. The pressure difference between the exhaust pipe and the atmosphere is one possible cause of the problem.

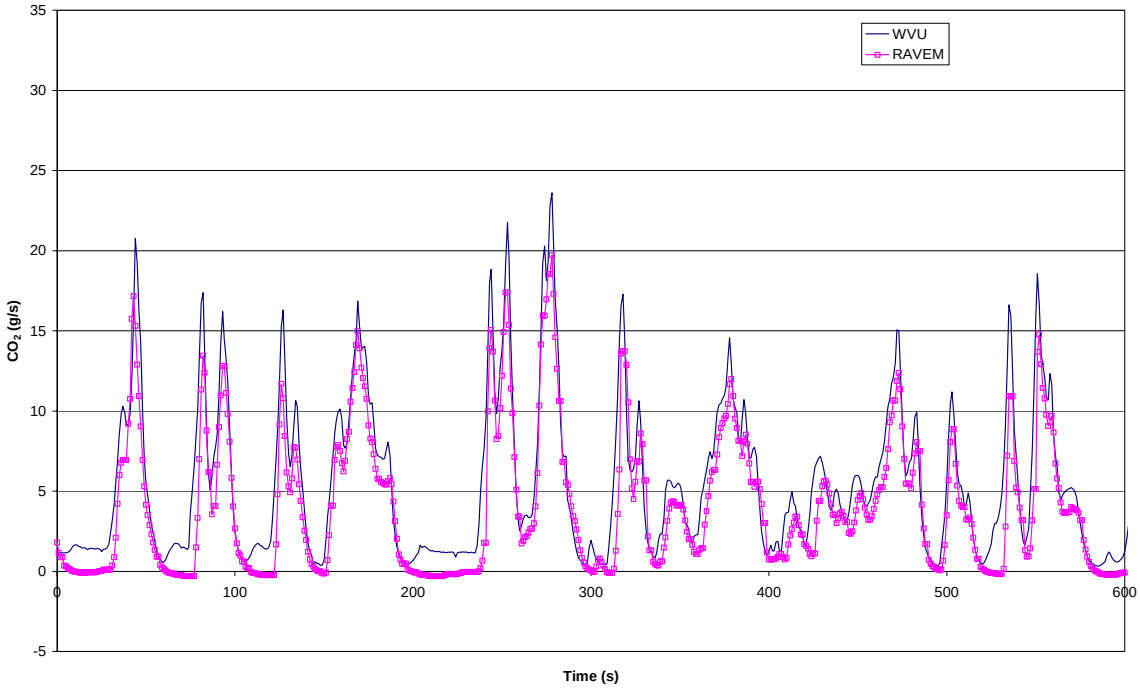

Figure 17 - Continuous CO_2 data from the WVU and RAVEM systems during the first 600 seconds of the European Transient Cycle.

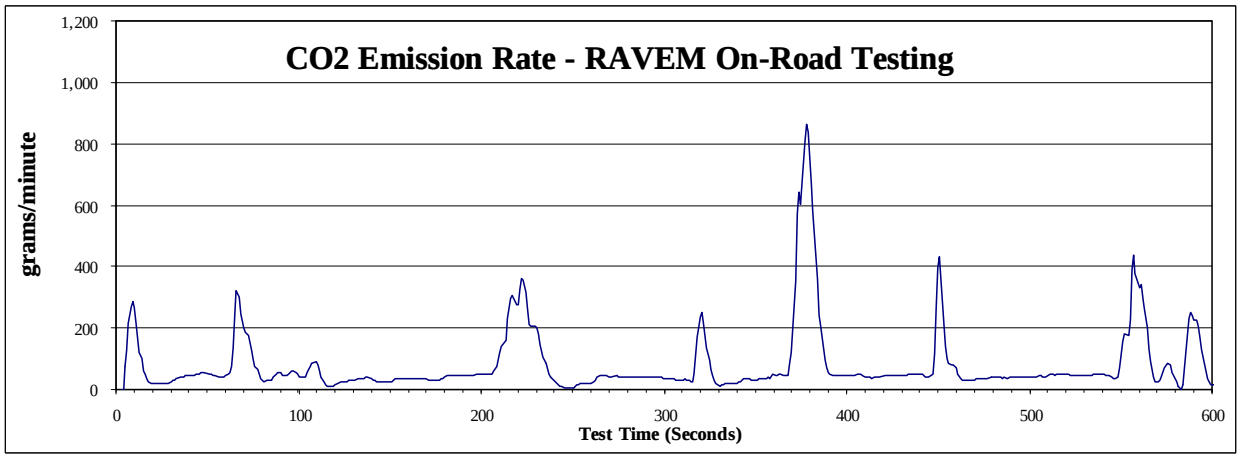

Figure 18 - Continuous CO_2 data from the RAVEM system during the first 600 seconds of an on-road emission test

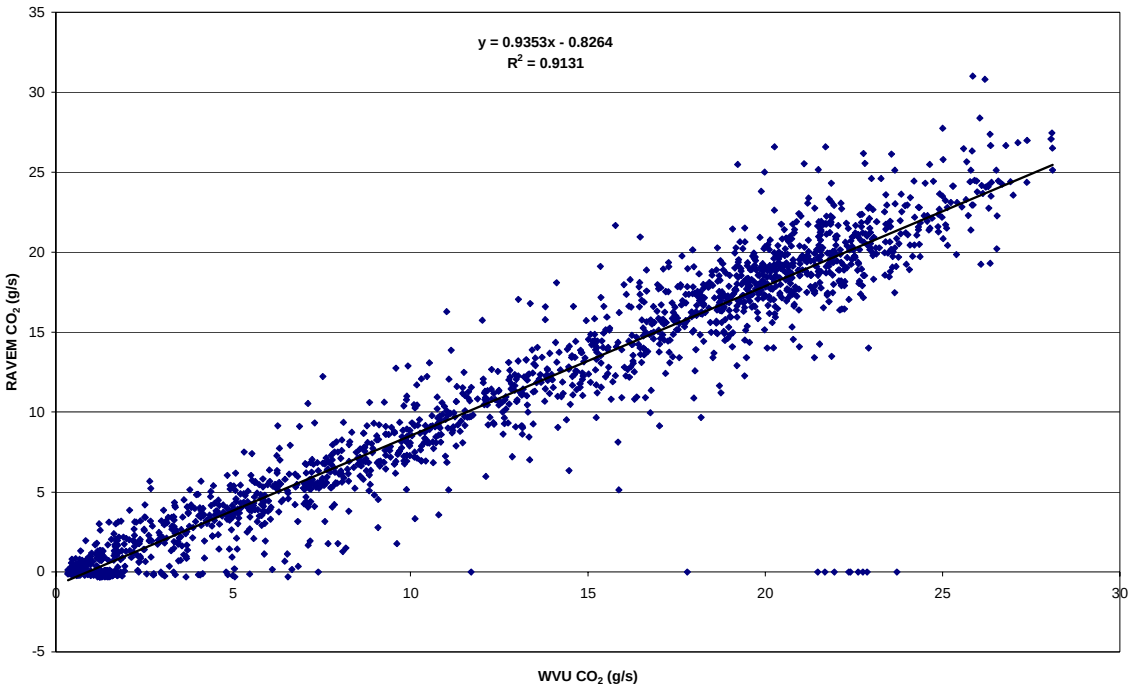

Figure 19 - Linear regression on CO_2 data from the entire 1800 seconds of the ETC (Figure 17 shows only the first 600 seconds of data from that test).

Correlation Discussion

Twenty six (26) tests were completed where the WVU and RAVEM emissions measurement systems were used. Of these, eight used the defective Mx01 probe, and are shown as yellow triangles in Figure 11 through Figure 13. The remaining valid tests are shown as blue diamonds in the figures, and were included in least-squares analysis leading to the best-fit lines in each figure.

CO_2 data are a close reflection of fuel consumption. The RAVEM data were, on average, 18% lower than the WVU data. This was established by preparing a parity or correlation plot between the RAVEM and WVU data and performing a linear regression on the data with a forced zero intercept. The CO_2 data also showed some scatter about the regression line. The greatest percentage difference between WVU and RAVEM CO_2 data was 33%. As noted earlier, the single measurement of mass fuel consumption during the correlation testing agreed closely with the RAVEM CO_2 measurement, and was 20% less than the WVU CO_2 measurement.

Subsequent to this test program, measurements of mass fuel consumption were also conducted in a number of on-board emission tests, on both CNG and diesel buses. These results, shown in Table 4, showed close agreement (± 5%) between the RAVEM results and the fuel consumption as measured by change in mass of the fuel tank.

WVU employed two NO_X analyzers throughout the test program. In all cases when both analyzers were in NO_X mode (as opposed to one in NO_X mode and one in NO mode), the agreement between the two analyzers was outstanding. For WVU and RAVEM comparison, NO_X was treated in a similar fashion to CO_2 and the first NO_X analyzer (NOX1) was used. NO_X was 16% lower on RAVEM than WVU and the greatest difference was 32%.

Correlation between RAVEM and WVU carbon monoxide emissions was poorer than correlation for NO_X and CO_2. CO values are difficult to quantify accurately for electronically managed diesel engines because they are characterized primarily by a low CO concentration level, with intermittent spikes of high CO concentration. In addition, CO measurements are subject to interference from both CO_2 and water vapor, with different analyzers responding to these interferences in different ways. The CO concentrations measured in this test program were extremely low. As normal products of combustion, both CO_2 and water vapor were present in the exhaust gas in much larger concentrations than the CO concentrations measured (although both the WVU and RAVEM system include provisions to remove water vapor from the sample reaching the CO analyzer, neither of these provisions would be expected to be 100% effective). Thus, it would not be surprising if the CO concentrations measured by the two analytical systems were to differ. For tests where WVU recorded less than 25 g/cycle of CO, the RAVEM system most often reported values which were zero or negative, which strongly suggests that the observed differences are at least partly due to differing response to the interfering species present.

The correlation between RAVEM and WVU particulate matter emissions was fair (R^2 = 0.85) with RAVEM measurements being about 43% lower on average than WVU. The correlation between the WVU TEOM and WVU filter offered better agreement (R^2 = 0.98) than between the WVU filter and the RAVEM PM measurements (R^2 = 0.86).

Inspection of the NO_X and CO_2 data reveals a similar difference between RAVEM and WVU. This suggests that the two systems differ as a result of flow measurement (e.g. to the measurement of CVS flowrate) rather than due to analyzer differences. Data were re-examined as a ratio of each species to the CO_2 mass. This is similar to examining the emissions in fuel specific units. The NO_X/CO_2 ratio measured by RAVEM and WVU was, on average, very close with a slope of 1.02 (R^2 = 0.90). The CO correlation was not substantially improved through using a ratio with CO_2, suggesting that there was a second cause for disagreement between the WVU and RAVEM methods.

Comparison of PM/CO_2 data showed no substantial improvement in the correlation when compared to PM mass, but the slope of the correlation line was increased from 0.57 to 0.71. The 20% difference between the two slopes is very similar to the ratio of NOx and CO_2 emissions for the two systems, and is thus likely ascribable to the same difference in flow measurement. The remaining 29% difference in PM measurements is likely due to differences in the two PM sampling systems. Recent correlation testing between the EF&EE RAVEM system and the full-flow CVS system at the University of California at Riverside showed the RAVEM data to average about 25% lower than the full-flow CVS system; whereas CO_2 and NOx measurements were nearly the same between the two systems.

It is not surprising that a systematic difference would exist for the PM masses because the capture of PM is known to be highly sensitive to the filter used, the filter face temperature, and the filter face velocity. Also, the nature of dilution and dilution ratio affect particulate formation. There are also important differences in the surface-to-volume ratios between the two systems, providing a greater opportunity for PM loss due to deposition on the tunnel walls. After factoring out the difference in CVS flow measurements, the remaining difference is similar to that observed between the WVU TEOM and filter measurements.

It was also noted that the highest percentage disagreements between WVU and the RAVEM system occurred for the lowest PM masses. Errors can arise when PM mass is low due to the limitations of filter weighing equipment and due to PM artifacts created by the sampling and dilution system.

Conclusions

- RAVEM mass CO_2 data were, on average, 18% lower than the WVU values. On the other hand, the RAVEM data were very close to the single mass fuel consumption measurement carried out during the program. Fuel mass measurements during a number of subsequent on-road emission tests have also shown good agreement with the RAVEM results.
- RAVEM mass NO_X data were, on average, 16% lower than the WVU values.
- RAVEM NO_X/CO_2 ratios corresponded reasonably with the WVU ratios.
- RAVEM mass CO data were, on average, 34% of the WVU values. These measurements appear to be affected by water and CO_2 interference at the very low CO concentrations observed. Measurements at higher CO concentrations (e.g. for gasoline vehicles) would not necessarily show the same ratio.
- For WVU CO values of less than 25 g/cycle, most RAVEM CO values were at or below 0 g/cycle.
- RAVEM mass PM data were, on average, about 57% of the WVU PM values.
- The correlation between the two WVU NO_X analyzers was high (R^2 = 0.995).
- The WVU TEOM and filter methods correlated well (R^2 = 0.977).
- The WVU TEOM measured 76% of the mass found from the WVU filter, on average.

Subsequent to the correlation tests between the RAVEM system and the WVU laboratory, EE&FE performed additional fuel and CO2 recovery tests and refined the QA/QC measures that will be instituted when the RAVEM system was in use. Details regarding the additional testing and QA/QC measures are contained in an appendix to this report.

Recommendations

The RAVEM system has been identified for further use in verifying the emissions from buses in Mexico City. This report has addressed concerns over a RAVEM leak between the CVS blower and thermal mass flow meter, a RAVEM probe leak, and the fact that this was only the second RAVEM system to be produced. A review of continuous data has shown that the RAVEM carbon dioxide level fell to zero at idle. As a result, it is recommended that additional correlation testing should be conducted between a seasoned RAVEM system and a WVU Transportable Laboratory, in Morgantown, WV. The proposed test schedule is discussed below.

Following independent setup and quality control checks of both the WVU and EE&FE equipment, steady-state tests should be performed using a heavy-duty vehicle on the dynamometer, with simultaneous measurement by EE&FE and WVU. Idle, 20mph and 40mph continuous operation would provide suitable exhaust flows. This should be repeated three times, and data should be screened to determine agreement between the two systems before proceeding further. Fuel consumption should be measured gravimetrically on the 20mph and 40mph steady-state runs to check both systems using a carbon balance. In addition, background gaseous and PM measurements should be compared for the two systems.

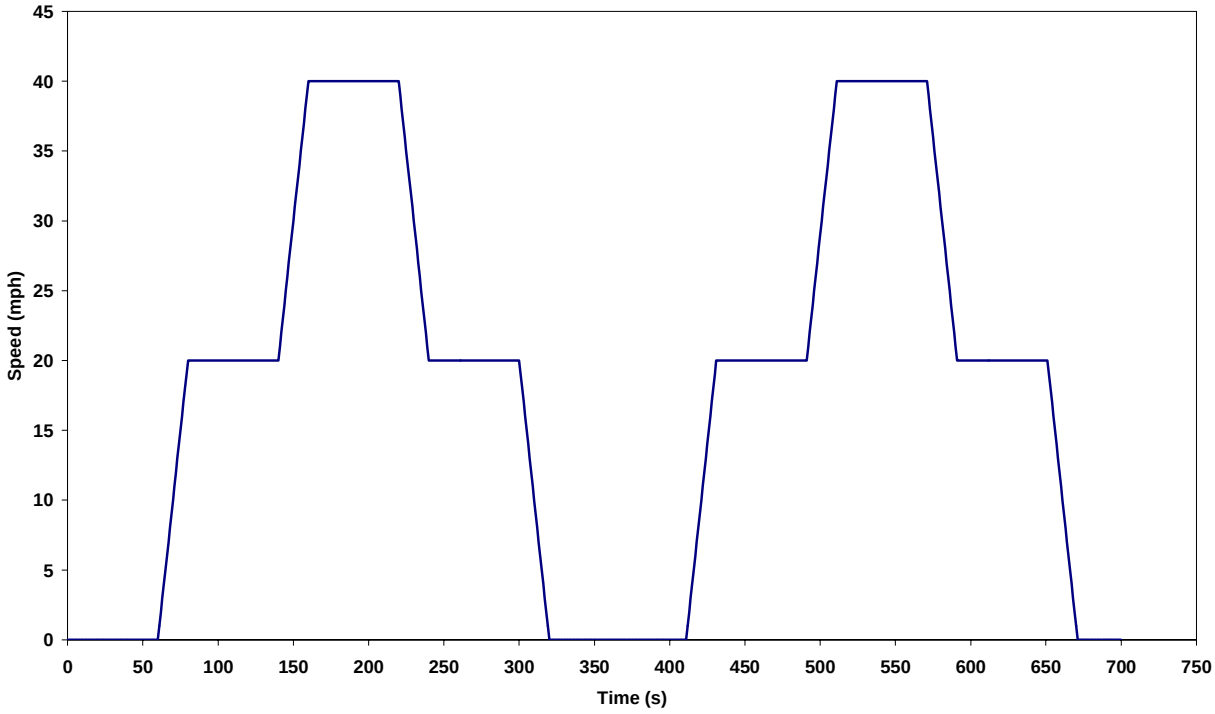

Figure 20: Geometric driving cycle for comparison of WVU and RAVEM systems.

Three repeats of a "geometric" cycle should be performed. This cycle should include both steady-state and transient portions to verify the ability of the RAVEM diluter to follow the transients successfully. A candidate cycle is shown in Figure 20. If deviation between the systems is identified, testing should not proceed further unless the cause is identified, and either rectified or accepted as best practice.

Last, three repeats of an accepted transient cycle, such as the ETC or UDDS, should be performed and emissions should be measured by WVU and EE&FE to yield both cycle-averaged and continuous data. One additional cycle should be run with a passive catalyzed exhaust particulate filter in place, both to assess the measurement of nitrogen dioxide and to assess the effect of low PM levels on measurement accuracy.

The results should be compiled in a report that compares the two systems and projects the RAVEM accuracy for use in Mexico City testing.

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6. C.S. Weaver and L.E. Petty “Reproducibility and Accuracy of On-Board Emission Measurements Using the RAVEM™ System “, SAE Paper No. 2004-01-0965, March, 2004.

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8. 40 CFR 86, Subpart N “Emission Regulations for New Otto-Cycle and Diesel Heavy-Duty Engines; Gaseous and Particulate Exhaust Test Procedures”.

Appendix A – Laboratory Description

Emissions from the test vehicles were measured by the West Virginia University Transportable Heavy-Duty Vehicle Emissions Laboratory (TransLab) in Morgantown WV. The WVU Transportable Laboratories were constructed to gather emissions data from in-use heavy-duty vehicles. Detailed information pertaining to the design and operation of the laboratories can be found in technical papers [1, 2, 3]. The laboratory was a fully functional heavy-duty chassis dynamometer with constant volume sampling (CVS) capability that can be physically transported to a bus operations site to conduct emissions testing.

Dynamometer

The chassis dynamometer used for this research was mounted on a semi-trailer, with removable wheels, that can be lowered to the ground by hydraulic jacks. The vehicle to be tested was then driven onto the dynamometer rolls via ramps. In most chassis dynamometers the power is taken from a set of rolls upon which the vehicle is secured and driven. Large diameter rolls are not practical for a mobile unit. When small diameter rolls are used, tire slippage proves a problem by corrupting data and overheating tires. The WVU Transportable Chassis Dynamometer withdraws power by removing the outer wheels of each dual wheel set and installing an adapter that couples the vehicle drive axles directly to the dynamometer system via driveshafts (Figure 1). The vehicle was supported on free-spinning rolls which served to link the driven wheels and maintain the same speed on both sides of the vehicle. The dynamometer components, which are largely symmetrical on each side of the vehicle, consisted of power absorbers and sets of selectable flywheels. Different combinations of flywheels in the flywheel set were engaged to allow simulation of inertial loads representative of desired vehicle weight (Figure 2). The vehicle was driven through a speed-time cycle by a driver receiving a prompt on a screen while vehicle speed and load were recorded by encoders and strain gage torque transducers. The road load applied to the vehicle was determined by performing on-road coast downs for each vehicle. Part of the applied load due to energy was dissipated through parasitic losses of the rotating components, determined during a calibration procedure, and the remaining load was applied by the eddy current absorbers in closed loop control. Parasitic losses were determined using a coast down procedure.

Figure 1: Hub adapters connect the vehicle's drive axle to the power absorber unit.

Figure 2: Flywheels were used to simulate vehicle inertia.

Regulated Emissions Sampling Equipment

Most environmental agencies worldwide have identified particulate matter (PM), oxides of nitrogen, (NO_X) hydrocarbons (HC) and carbon monoxide (CO) as species that must be regulated and quantified. Additionally, in this program, carbon dioxide (CO_2) was sampled since this species is a well-established indicator of engine fuel consumption and is also a major greenhouse gas. The exhaust from the test vehicle was ducted into a total exhaust, critical flow venturi-constant volume sampler (CFV-CVS) and mixed with HEPA filtered ambient air in the primary dilution tunnel. The dilution tunnel measured 18 inches (45cm) in diameter 20 feet (6.1m) in length. The flow rate of diluted exhaust was controlled and measured precisely by a critical flow venturi (CFV) system. Gaseous samples were drawn from the dilution tunnel ten diameters downstream of the exhaust injection zone to allow thorough mixing in the turbulent region of the dilution tunnel. The diluted exhaust is sampled and analyzed in accordance with the procedures outlined in the CFR 40 Part 86 Subpart N [4]. The emission sampling, data acquisition and test control equipment was housed in a 22-foot box trailer. The diluted exhaust was analyzed using non-dispersive infrared (NDIR) detectors for CO and CO_2, and using chemiluminescent detection for NO_X. HC emissions were analyzed using a heated flame ionization detector (HFID). The gaseous data were available as continuous concentrations throughout the test, and the product of concentration and dilution tunnel flow were integrated to yield emissions in units of grams per mile (g/mile). In the case of CO, the laboratory operates two separate analyzers calibrated for different ranges. The lower ranged CO analyzer is set to capture the low-level CO emissions which occur during a majority of testing on diesel vehicles while the higher ranged CO analyzer is set to capture the spikes which occur during transient operation. PM was collected using 70-mm fluorocarbon coated glass fiber filter media and were determined gravimetrically. Fuel efficiencies were determined using a carbon balance and exhaust emissions data. The laboratory is shown in Figure 3.

Figure 3: WVU Transportable Laboratory testing the Allison hybrid-electric bus.

Non-Regulated Species Sampling

The non-regulated species measured in this program included nitrous oxide (N_2O) and aldehydes. The aldehydes were quantified under a separate agreement by Environment Canada, and so only N_2O emissions are discussed in this report. For each test, an integrated bag sample was collected by a heated sampling system and subsequently analyzed using an Innova 1302 photoacoustic analyzer. The 1302 sample train consisted of a heated stainless steel sample line, a heated head sample pump, a flow controller and a heated enclosure housing a 10-liter Tedlar® sample bag. Both the sampling line and bag enclosure were heated to 150° F to prevent condensation. Following collection, a sample was drawn from the Tedlar bag through the 1302 analyzer to determine N_2O and CO_2 levels. CO_2 data measured using the Innova 1302 were compared with the CO_2 data from the emissions laboratory's NDIR analyzer to confirm that the 1302 analyzer was functioning properly and to check agreement between the 1302 instrument and the laboratory. The Innova 1302 system is shown in Figure 4.

Figure 4: Innova 1302 Photoacoustic analyzer and sampling system.

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Dr. Víctor Hugo Páramo
Director General de Gestión Ambiental del Aire
Secretaría del Medio Ambiente
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REF: Quality Assurance for RAVEM Testing

Dear Dr. Páramo:

In 2004, Engine, Fuel, and Emissions Engineering, Inc. (EF&EE) supplied a RAVEM on-board emission measurement system to the Gobierno del Distrito Federal (GDF). Since October of that year, we and our local partner, Ambientalis, have been using the GDF's RAVEM system to measure emissions from buses in Mexico City. We also participated in a correlation program between the RAVEM system and the West Virginia University transportable emission measurement system. In the course of these test programs, questions have arisen concerning the accuracy of the emission measurements made to date with the RAVEM system, and how we can assure the accuracy of future measurements. This letter addresses those questions. It describes both the quality assurance (QA) measures we have already implemented, and the additional measures that we propose to implement as a result of the experiences to date.

Existing quality assurance measures

The questions that have arisen focus on the RAVEM's constant volume sampling (CVS) system. Three quality assurance procedures are presently used to check the accuracy of the CVS system. First, the venturi meter that controls the CVS flow is checked daily against a thermal mass flow meter that is built into the RAVEM. Second, the accuracy of the thermal mass flow meter is checked periodically by conducting CO_2 recovery tests. In this test, CO_2 is released from a pre-weighed cylinder into the sample inlet of the RAVEM system. The change in mass of the CO_2 cylinder is compared to the mass of CO_2 measured by the RAVEM. These measurements normally agree within two percent. This checks the accuracy of the CVS flow measurements, gas sampling system, and CO_2 analyzer. It can be conducted either with the RAVEM mounted in a vehicle or in the laboratory.

The third CVS system check is fuel recovery, which is carried out on a vehicle or engine, normally under transient conditions. In this test, we reroute both the fuel supply and return lines from the engine to a portable fuel tank. The tank is weighed before and after the

emission test, and we compare the change in weight of the fuel tank with the mass fuel consumption calculated from the RAVEM results by carbon balance. These numbers generally agree within 4%. This checks the isokinetic proportional sampling system as well as the CVS, gas sampling system, and CO_2 analyzer.

The fuel recovery test requires modifying the vehicle's fuel system, and any leaks (or any fuel flow-paths that are not accounted for) will invalidate the results. For this reason, it is best to conduct it on a dedicated vehicle, so that the fuel system modifications have to be made only once. In our original proposal to supply the RAVEM system, we specified that GDF should provide a vehicle to be used for fuel recovery testing. Unfortunately, you were unable to do so. Thus, to carry out fuel recovery tests, we have had to modify the fuel systems of the buses in the test program. This has limited the number of fuel recovery tests that it has been possible for us to do.

Results of QA Tests to Date

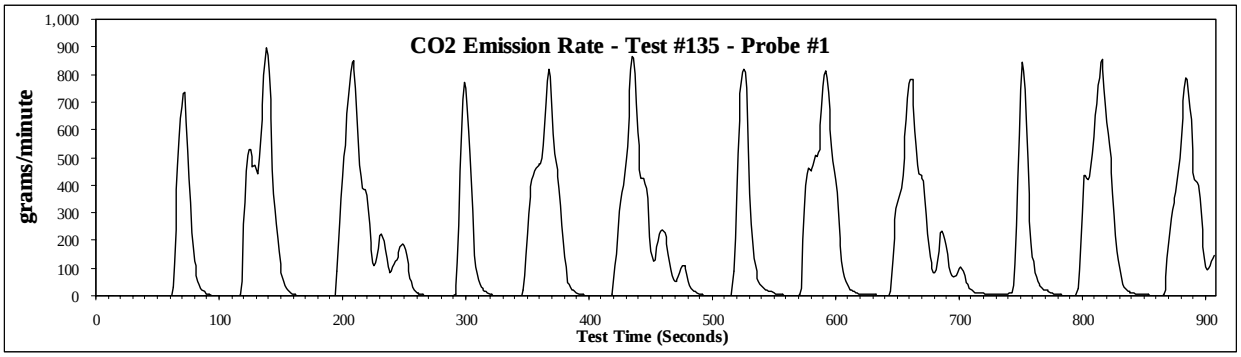
CO_2 recovery tests were conducted when the RAVEM first entered into service, and periodically thereafter. The initial tests showed a discrepancy of 7% between the mass of CO_2 measured by the RAVEM and the change in mass of the CO_2 cylinder. This was eventually determined to be due to a leak due to a missing setscrew between the venturi and the thermal mass flow meter. The problem was found and fixed in early January, and the affected test results have been corrected for the resulting miscalibration. CO_2 recovery tests conducted since that time have all shown agreement within the accuracy of the cylinder weight measurement.

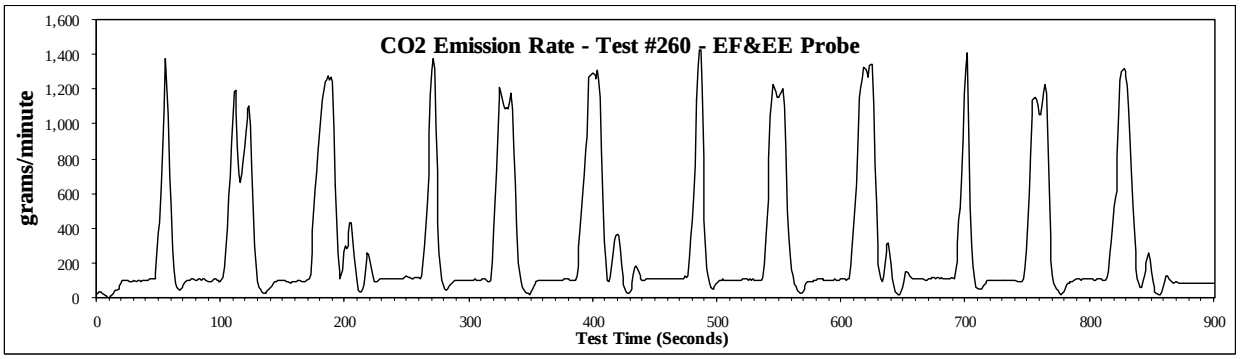
Fuel recovery tests were conducted on two buses shortly after the RAVEM went into service, and showed fuel recovery discrepancies of 12% and 24%, indicating that the RAVEM was under-measuring the real emissions. The source of the error was eventually determined to be a defect in MX01, one of the sample probes supplied with the system. As part of the diagnostic process, this probe was replaced with a known good probe from EF&EE's own RAVEM system. Subsequent fuel recovery tests using the EF&EE probe were conducted in November, 2004 (in conjunction with the WVU correlation testing), January 2005, and February 2005. Except for one test that may have been affected by a fuel system leak, all showed agreement within 5% (including a repeat test 3 days later). Another fuel recovery test in February, 2005 used one of the large-diameter probes supplied with the RAVEM system, and showed agreement within 1%. We plan to carry out additional fuel recovery tests in the near future.

Pressure leaks affecting the proportional sampling system

The problem with probe MX01 appears to have been a pressure leak in one or more of the differential pressure lines. The RAVEM's isokinetic proportional sampling system works by measuring the static pressure differential between the inside and the outside of the sampling probe, and adjusting the sample flow rate until this difference is zero. Any leak in the pressure lines between the probe and the differential pressure sensor will affect the differential pressure measurement, and thus the accuracy of the proportional sample. The error is exacerbated when the pressure in the exhaust pipe differs significantly from atmospheric pressure, as occurred during the WVU correlation testing.

The magnitude of the differential pressure signal increases with the square of the exhaust velocity, so that it is low at idle and high at higher RPM. Thus, any error in the sampling system is likely to be most visible at idle. In the case of probe MX01, we observed that the sampling system control at idle sometimes became unstable. Exhaust emissions at idle were under-sampled, so that the measured emission rate went to zero after correcting for background pollutant concentrations. The two figures below compare the mass emission rates measured using the faulty probe MX01 to those measured using the EF&EE probe.





EF&EE supplied a differential pressure calibrator with the RAVEM system, in order to detect potential leaks in the pressure lines. Since this calibrator replaces the probe assembly, however, it could not detect the leaks in the probe itself, or in the quick-connect couplings between the probe and the pressure lines.

To make it easier to detect such leaks in the future, EF&EE has developed a system of solenoid valves to check for such leaks *in situ*, immediately before or between emission tests. This system of valves connects the four pressure lines to the differential pressure sensor in the following four ways:

1. Normal operation – lines to the two inside pressure taps connected together and to the "high" side of the differential pressure sensor. Lines to the two outside pressure taps connected together and to the "low" side of the sensor.

2. Check inside – the line from one inside tap connected to the high side, and the other to the low side of the pressure sensor. Any difference in pressure readings between the two lines may indicate a leak in one of them. The outside pressure taps are isolated.

3. Check outside -- the line from one outside tap connected to the high side, and the other to the low side of the differential pressure sensor. The inside pressure taps are isolated. Any difference in pressure readings between the two lines may indicate a leak, or possibly misalignment between the probe and the exhaust velocity vector.

4. Short circuit – the high and low sides of the pressure sensor are connected together, and isolated from all external pressures. This setting is used to check and set the "zero" calibration of the pressure sensor.

We have successfully tested this configuration on our RAVEM development system, and plan to retrofit it to the Mexico City RAVEM system very soon.

WVU Correlation Testing

Because of delays in customs, the WVU correlation testing had to take place shortly after we delivered the RAVEM system, and before we had found and corrected all of the start-up problems with the RAVEM system. Thus, the correlation tests on the first few vehicles were conducted using probe MX01, which we subsequently determined to be defective. In addition, the CVS calibration during the entire WVU correlation program was affected by the missing setscrew, which caused the CVS flow – and thus the emission results – to be undercalculated by seven percent.

In both cases, the existence of these problems had been pointed out by the regular quality control tests undertaken during startup of the RAVEM system. The CVS leak was identified by CO_2 recovery testing, while the problem with the MX01 probe was identified by fuel recovery testing. Unfortunately, we were unable to identify and correct the specific causes of these problems in time for the start of the correlation testing with WVU.

As the joint WVU/EF&EE correlation report documents, even after discarding the tests affected by the defective probe, and correcting for the 7% miscalibration due to the missing setscrew, we were still left with a discrepancy between the RAVEM and WVU results. Although RAVEM and WVU results correlate well, the RAVEM mass CO_2 data were, on average, 18% lower than the WVU values. The RAVEM NOx data averaged 16% lower than the WVU values; and the PM data averaged 43% less.

The fact that the NOx and CO_2 differences are so similar and consistent indicates that the discrepancies between the two systems are likely due to a difference in the CVS systems rather than in the gas analyzers. The difference in PM measurements is likely due to a combination of the CVS difference and differences in the PM collection system. PM measurements are known to be sensitive to differences in filter flow rate, filter conditioning and weighing conditions, and background measurements, among other factors. After factoring out the apparent difference in the sampling systems, the remaining PM discrepancy is about 29%, which is quite close to the difference between the WVU filter measurements and WVU's own TEOM system.

The one fuel recovery test carried out during the WVU correlation program shows good agreement between the RAVEM results and the measured change in mass of the fuel tank, suggesting that the cause of the discrepancy could be in the WVU system. However, the

results of propane recovery tests and detailed analysis of the data indicate that the WVU CVS flow measurements were accurate. We have not been able to resolve this contradiction, and thus we have been unable to determine the source of the discrepancy. The results of recent correlation tests between the EF&EE RAVEM system and the University of California at Riverside's full-flow CVS system are may shed light on this issue, once they are released by U.C. Riverside (we expect that to happen within a few weeks). Otherwise, the WVU/EF&EE correlation report recommends that additional testing be carried out between the mature (fully-debugged) RAVEM and the WVU system.

Implications for Ongoing Measurement Programs

Fortunately, it is not necessary to fully resolve the discrepancies in the correlation program in order to conclude that the data now being generated by the RAVEM system are accurate. This is because:

1. We know from fuel recovery tests on a number of buses that the RAVEM system is accurately measuring transient CO_2 emissions in our on-road tests. We will continue to check this on an ongoing basis, by carrying out fuel periodic fuel recovery tests.
2. The results of the correlation program show that the ratio of NOx to CO_2 measured by the RAVEM system agreed well with that measured by WVU. Since the CO_2 emissions being measured accurately, the measured NOx emissions must be accurate as well.
3. The results of the correlation program show that the ratio of PM to CO_2 ratio measured by the RAVEM system correlated well with that measured by WVU, even though the slope of the correlation line was not 1:1. Thus, to estimate the PM values that the WVU system would have measured, we need only divide the measured value by 0.71, the slope of the correlation line.

To assure the ongoing accuracy of the emission measurements, we propose to formalize the following QA schedule for the isokinetic sampling and CVS systems:

During/after every test

- Check that the throttle controlling CVS flow remains in the normal range, and that the isokinetic proportional sampling system appears to be operating normally
- Check that the plot of pollutant mass flow rates vs. time appears normal, that idle emissions are stable and greater than zero, and that peak CO_2 emission rates are consistent with engine rated power and brake-specific fuel consumption (EF&EE will incorporate changes in the control software to plot these data on the screen at the end of the emission test)

Upon installing the RAVEM in the vehicle, and at least every three tests thereafter

- Check CVS venturi calibration against the thermal mass flow meter
- Check differential pressure sensor zero reading and integrity of the differential pressure lines using the new solenoid valve system

At least weekly

- Check differential pressure lines using the calibrator system
- Confirm CVS system accuracy by CO_2 recovery test

At least monthly, and whenever practical upon introducing a new probe or exhaust configuration

- Perform fuel recovery tests at idle and in normal transient driving (by doing fuel recovery at idle – the most sensitive mode – as well as in normal driving, we will enhance the sensititivity of the check).

By carrying out the checks as outlined above, I am confident that we can assure the reliability and accuracy of the RAVEM measurements on a continuing basis.

Please let me know if you have any questions or comments on this analysis, or on our proposed QA schedule.

Sincerely,

Christopher S. Weaver, P.E.
President