REPORT

Correlation between the Mexico City Government's RAVEM System and West Virginia University's Transportable Heavy Duty Emissions Laboratory

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Introduction

In October and November 2004, West Virginia University conducted a research study funded by the Mexico City Secretariat of Environment (Contract GDF-SMA-SEF-SC-027-04). The objective of this study was to characterize the vehicle emissions from a variety of transit buses using both current and advanced engine control and aftertreatment technologies and low emissions fuels in Mexico City, Mexico. Emissions were measured from nine transit buses including six powered by diesel engines, two powered by natural gas engines and one employing a diesel-hybrid powertrain.

During testing on five of the test buses, the Ride Along Vehicle Emissions Measurement (RAVEM) system from Engine, Fuel and Emissions Engineering Inc., was used to measure emissions in parallel with the West Virginia University Transportable Emissions Laboratory. Results of the correlation between the West Virginia University Transportable Emissions Laboratory and the RAVEM System were reported in a report issued to the Mexico City Secretariat of Environment. The correlation report noted several discrepancies between the two systems.

- RAVEM mass CO_2 data were, on average, 18% lower than the WVU values. On the other hand, fuel mass measurements during a number of subsequent on-road emission tests have 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 appeared 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.
- RAVEM mass PM data were, on average, about 57% of the WVU PM values.

Among the factors possibly contributing to these discrepancies were the fact that the RAVEM system was new at the time, and had not been fully debugged. The RAVEM system was subsequently used extensively to measure in-use emissions from buses in Mexico City. The question has therefore arisen of whether the mature RAVEM system would exhibit better correlation with the WVU system. To assess this question, Engine, Fuel, and Emissions Engineering, Inc. was contracted to plan and carry out a correlation study between the Mexico City RAVEM system and the WVU transportable emission testing laboratory.

Technical Approach

EF&EE and its Mexico City subcontractor, Ambientalis, arranged to ship the RAVEM system from Mexico City to EF&EE's laboratory in California for routine checks. EF&EE then transported the RAVEM system to the West Virginia University campus in Morgantown, West Virginia.

Emission testing was performed on a 1995 Mack CH613 road tractor. Specifications for the test vehicle are given in Table 1. The testing was conducted from November 28 to December 1, 2006.

Table 1: Test vehicle specifications

Truck Model	Mack CH613
VIN Number	1M1AA13Y9SW054437
Serial	054437
Vehicle Model Year	1995
Engine Model	Mack E7400 V-MACII [1]
Engine Model Year	1995
Engine Serial No.	5A0796
ECM Serial No.	1989371
Displacement	728 cu. in. (11.9L)
Rated Power	400 bhp @1800 rpm
Peak Torque	1460 lb-ft @ 1250 rpm
Emissions Compliance	1996 U.S. EPA
Transmission	Eaton Fuller 10-speed
[1] This engine was manufactured as an E-7-350 V-MAC II built in 1995. It was upgraded to an E7-400 V-MACII on March 12, 1999 by changing to a 736GB343-P7 injection pump and V-MAC data software set 1MS548-P7.	

The tractor used for these tests was equipped with a manual transmission, which resulted in abrupt changes in engine load during gear shifts. This required that RAVEM's isokinetic sampling system be set for a relatively slow response rate to avoid oscillation introduced by the rapid load changes during shifts.

The test plan agreed with WVU occupied four days, as follows:

Set-up and Pre-Test Quality Control Checks

Day 1:

- HFID Response Optimization
- HFID Oxygen Interference Check
- NOx Converter Efficiency Checks
- NOx Analyzer CO_2-H_20 Quench Check
- CO Analyzer CO_2/Water Interference Checks
- CO_2/CO System Probe Flood
- PM mass Flow Controller Calibration Checks
- Propane Injections

- Calibrate Gaseous Emissions Analyzers

Day 2:

- Install the Mack tractor on the chassis dynamometer
- Perform pre-test ambient background
- Set Inertia Weight to 56000 lb
- Perform coast downs to determine road load profile
- Perform 3 repeat runs of Idle Mode (20 minute duration with 10 minute soaks)
- Perform 3 repeat runs of 20-mph steady-state test (20-minute duration with 10 min soaks between repeat runs)
- Perform 3 repeat funs of 40-mph steady state (20-minute duration with 10 min soaks between repeat runs)
- Fuel consumption will be measured gravimetrically on the 20-mph and 40-mph steady states to verify both systems using a carbon balance
- Perform post-test ambient background
- Review data to determine agreement between RAVEM and WVU Laboratory before proceeding further
- Perform 3 repeat runs of the heavy-duty UDDS transient test cycle
- Measure fuel consumption gravimetrically during UDDS test cycles.

Day 3:

- Perform pre-test ambient background
- Install DPF filter onto vehicle. The filter was an Engelhard DPX™ catalyzed diesel particulate filter that was originally sized and specified for the 1995 Mack.
- Perform 3 repeat runs of the heavy-duty UDDS transient test cycle
- Measure fuel consumption gravimetrically during UDDS test cycles.
- Perform post-test ambient background
- Remove DPF from test vehicle
- Remove vehicle from chassis dynamometer

Day 4:

- Perform pre-test ambient background
- Degrade the PM emissions of the 1995 Mack tractor by either bleeding off turbocharger boost pressure or restricting the air intake to increase PM emissions levels.
- Perform 3 repeat runs of the heavy-duty UDDS transient test cycle
- Perform post-test ambient background

The UDDS transient cycle used for these tests is a challenging one for any portable emission measurement system – involving extensive idle operation punctuated by hard accelerations, as diagrammed in Figure 1.

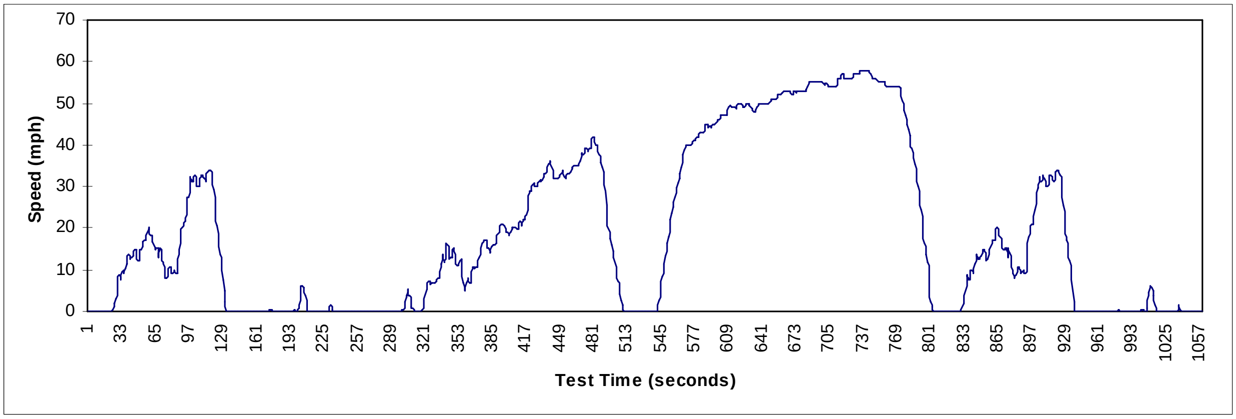

Figure 1: Speed vs. time for the UDDS driving cycle

Results

The RAVEM results for the emission tests are summarized in Table 2. The NOx data (cNOx) include correction for humidity calculated according to EPA regulations. Emissions of NOx, CO, and CO_2 were determined both as the integrated sum of second-by-second measurements and on the basis of Tedlar bag samples integrated over the entire test. For NOx and CO_2, the two measurements agree well. The CO concentrations measured were so low that analyzer drift over the test period had a significant effect on the results. Thus, the modal emission data for CO are not reliable at these low concentrations.

Table 2: Emission test results for the Mexico City RAVEM system

		Length	Distance	Bag Emissions (g/mi)				Modal Emiss. (g/mi)		
Test No.	Test Date/Time	(sec)	(mi)	CO_2	CO	cNOx	PM	CO_2	CO	cNOx
MX0703	11/29/2006 6:37	1,201	12.6	1,078	0.2	23.88	#N/A	1,097	0.3	25.68
40 MPH Steady-State										
MX0704	11/29/2006 7:14	1,142	12.6	991	0.3	22.05	0.102	1,025	0.3	23.10
MX0705	11/29/2006 7:48	1,141	12.6	970	0.2	21.39	0.073	1,006	0.5	22.36
MX0706	11/29/2006 8:23	1,141	12.6	947	0.1	20.86	0.088	945	-0.2	21.93
20 MPH Steady-State										
MX0707	11/29/2006 8:58	1,141	6.3	785	0.5	16.27	0.048	788	-0.2	16.64
MX0708	11/29/2006 9:34	1,139	6.3	788	0.8	16.36	0.052	804	0.5	16.79
MX0709	11/29/2006 10:09	1,141	6.3	795	0.7	16.48	0.069	806	1.0	16.94
Idle										
MX0710	11/29/2006 10:44	1,199	1.0	1,336	2.2	21.82	0.426	1,368	-0.6	21.83
MX0713	11/29/2006 11:19	1,201	1.0	1,393	1.3	21.48	0.282	1,439	-0.8	21.82
MX0714	11/29/2006 11:53	1,200	1.0	1,359	0.9	22.58	0.603	1,410	0.1	23.27
Baseline UDDS										
MX0715	11/29/2006 12:31	1,069	5.5	1,944	2.0	21.48	#N/A	1,994	2.4	21.25
MX0717	11/29/2006 13:09	1,064	5.5	1,801	2.4	20.18	0.375	1,821	2.8	20.62
MX0718	11/29/2006 13:47	1,068	5.5	1,844	1.8	20.81	0.381	1,860	2.2	21.37
MX0719	11/29/2006 14:25	1,067	5.5	1,828	1.7	21.28	0.345	1,847	3.0	21.83
UDDS w DPF										
MX0720	11/30/2006 8:46	1,063	5.5	1,943	0.0	22.57	0.053	1,962	-0.8	23.19
MX0721	11/30/2006 9:24	1,061	5.5	1,891	-0.1	21.34	0.073	1,891	-0.4	21.55
MX0722	11/30/2006 10:01	1,061	5.4	1,901	0.0	21.28	0.097	1,911	-0.8	21.58
MX0723	11/30/2006 10:39	1,062	5.4	1,865	0.0	19.65	0.064	1,862	-1.1	19.66
UDDS w Turbo Air Bleed										
MX0724	12/1/2006 6:24	1,063	5.5	1,979	4.5	21.67	0.532	1,948	1.9	22.19
MX0725	12/1/2006 7:01	1,063	5.5	1,952	4.8	19.51	0.593	1,973	5.8	20.05
MX0726	12/1/2006 7:39	1,062	5.5	1,921	5.7	18.95	0.626	1,944	5.8	19.75
MX0727	12/1/2006 8:17	1,061	5.5	1,928	6.1	18.49	0.659	1,934	6.7	18.82

The fuel consumption during each test was recorded as the change in weight of a fuel drum placed on a scale. Fuel consumption could also be calculated from the sum of CO_2 and CO emissions measured by the RAVEM system. For these calculations, we assumed a fuel H:C ratio of 1.85 to 1, so that the fuel contained 86.6% carbon by weight. Table 3 compares the results of this calculation with the measured change in weight of the fuel tank.

Table 3: Carbon balance results for the RAVEM measurements

Test No.	Calc. Fuel (g)		Weighed Fuel (g)	Carbon Balance	
	Bag	Modal		Bag	Modal
MX0703	4,279	4,355	4,358	98.2%	99.9%
40 MPH Steady-State					
MX0704	3,932	4,069	3,950	99.6%	103.0%
MX0705	3,849	3,996	3,950	97.4%	101.2%
MX0706	3,756	3,745	3,863	97.2%	97.0%
20 MPH Steady-State					
MX0707	1,553	1,558	1,857	83.6%	83.9%
MX0708	1,561	1,592	1,904	82.0%	83.6%
MX0709	1,577	1,599	1,860	84.8%	86.0%
Idle					
MX0710	422	430	454	92.9%	94.8%
MX0713	439	453	409	107.5%	110.8%
MX0714	428	444	454	94.4%	97.8%
Baseline UDDS					
MX0715	3,354	3,441	3,496	95.9%	98.4%
MX0717	3,121	3,156	3,269	95.5%	96.5%
MX0718	3,194	3,222	3,360	95.1%	95.9%
MX0719	3,159	3,196	3,314	95.3%	96.4%
UDDS w DPF					
MX0720	3,347	3,378	3,450	97.0%	97.9%
MX0721	3,263	3,262	3,360	97.1%	97.1%
MX0722	3,263	3,278	3,360	97.1%	97.6%
MX0723	3,202	3,192	3,314	96.6%	96.3%
UDDS w Turbo Air Bleed					
MX0724	3,421	3,361	3,541	96.6%	94.9%
MX0725	3,382	3,421	3,541	95.5%	96.6%
MX0726	3,337	3,377	3,587	93.0%	94.1%
MX0727	3,343	3,355	3,768	88.7%	89.0%

As Table 3 shows, the measured and calculated fuel consumption data agree closely, except in the 20 MPH steady-state tests, where they differ by about 15%.

The emission test results reported by WVU are given in the appendix, and are summarized in Table 4. The NOx data shown in this table have also been corrected for humidity. In addition, for second and third tests of each series, the NOx2 analyzer was set to read NO, rather than NOx, so that it would be possible to determine the NO/NO_2 split. As expected, NO accounts for than 90% of the total NOx in all operating modes, except for the tests with the catalytic DPF in place. The DPF catalyst converted a significant fraction of the NO to NO_2.

Table 4 also shows the carbon balance calculations for the WVU data, calculated in the same way as for the RAVEM data in Table 3. Overall, the fuel consumption calculated from the WVU emission data corresponds closely to the change in weight of the fuel tank, except at idle, where the discrepancy is about 15-20%.

Table 4: Test results for the WVU Transportable Heavy-Duty Emission Laboratory

RAVEM Test No.	WVU Test No.	Emissions (g/mi)						Calc. Fuel	Weighed Fuel	Carbon Balance
		CO	NOx[1]	NOx[2]	HC	PM	CO_2			
40 MPH Steady-State										
MX0704	5015-2	0.68	22.1	21.7	0.18	0.133	979	3,891	3,950	98.5%
MX0705	5015-3	0.6	21.1	20.1 NO	0.17	0.072	949	3,772	3,950	95.5%
MX0706	5015-4	0.55	21.2	20.0 NO	0.18	0.077	930	3,693	3,863	95.6%
20 MPH Steady-State										
MX0707	5016-1	1.64	18.5	18.1	0.36	0.1	902	1,791	1,857	96.5%
MX0708	5016-2	1.6	18.4	16.7 NO	0.39	0.1	918	1,823	1,904	95.7%
MX0709	5016-3	1.63	18.5	16.7 NO	0.42	0.1	920	1,830	1,860	98.4%
Idle										
MX0710	5017-1	2.08	18.2	18.5	1.26	0.33	1158	367	454	80.8%
MX0713	5017-2	2.17	18.7	16.2 NO	1.58	0.48	1110	352	409	86.2%
MX0714	5017-3	2.38	19.7	17.1 NO	1.59	0.52	1186	376	454	82.9%
Baseline UDDS										
MX0717	5018-2	2.36	20.5	20.3	0.35	0.38	1841	3,191	3,269	97.6%
MX0718	5018-3	2.28	20.9	19.6 NO	0.29	0.34	1889	3,274	3,360	97.4%
MX0719	5018-4	2.22	21.4	20.2 NO	0.34	0.34	1847	3,195	3,314	96.4%
UDDS w DPF										
MX0721	5021-2	0.066	20.5	20.4	0	0.016	1839	3,174	3,360	94.5%
MX0722	5021-3	0.001	20.4	13.0 NO	0	0.011	1843	3,163	3,360	94.2%
MX0723	5021-4	0.111	18.7	11.8 NO	0	0.013	1813	3,112	3,314	93.9%
UDDS w Turbo Air Bleed										
MX0725	5024-2	4.43	19	18.7	0.28	0.69	1976	3,424	3,541	96.7%
MX0726	5024-3	4.58	19	17.8 NO	0.32	0.75	1955	3,394	3,587	94.6%
MX0727	5024-4	4.97	17.7	16.5 NO	0.34	0.88	1975	3,424	3,768	90.9%

Up to this point, the emissions data have been presented in terms of grams per mile, or grams per test in the case of the idle emissions. Since pollutant concentrations and emission measurements have no defined relationship to distance traveled, however, it is more it is more representative to express the results in grams per minute. Figure 2 plots the fuel consumption calculated from the RAVEM bag data vs. measured mass fuel consumption, while Figure 3 does the same for the RAVEM modal data. Figure 4 shows the corresponding plot for the emissions measured by the WVU system. As these figures show, the both the RAVEM and WVU carbon balance data correspond nearly 1-for-1 with the measured fuel consumption.

The RAVEM and WVU emission results can also be plotted against each other. Figure 5 compares the PM and bag gaseous measurements from the RAVEM system against the corresponding WVU data, while Figure 6 does the same for the RAVEM modal data. As would be expected from the carbon balance results, the RAVEM CO_2 measurements are about 11 to 12% higher than the WVU measurements, but the two data sets correlate well. The NOx data also correlate extremely well between the two measurement systems.

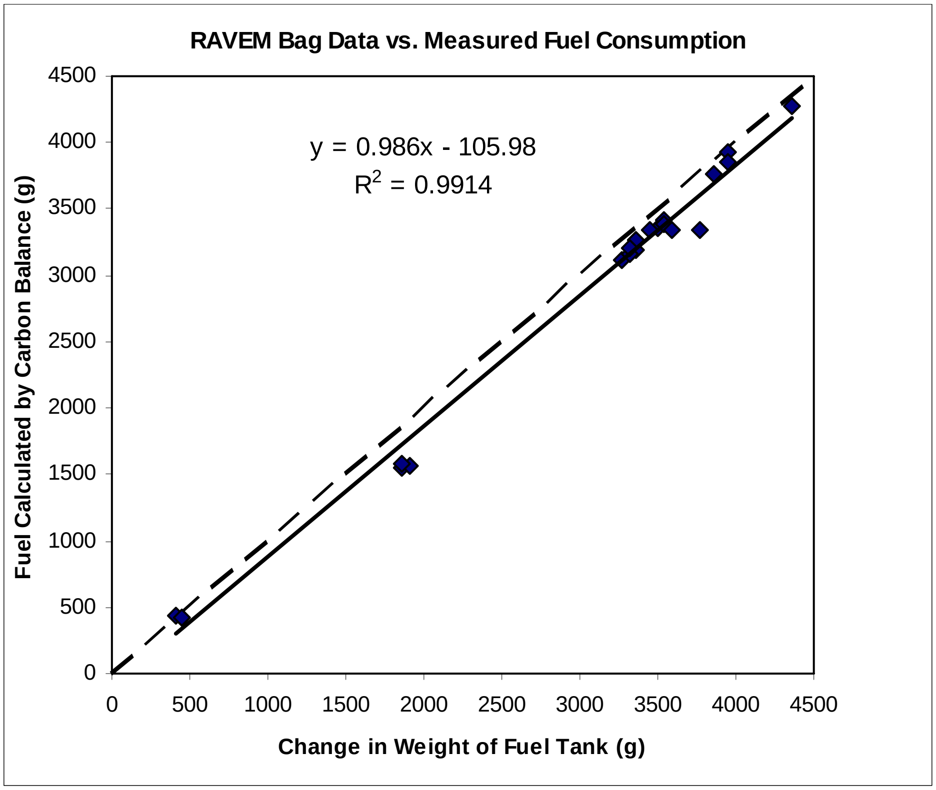

Figure 2: Fuel calculated from RAVEM bag data vs. measured fuel consumption

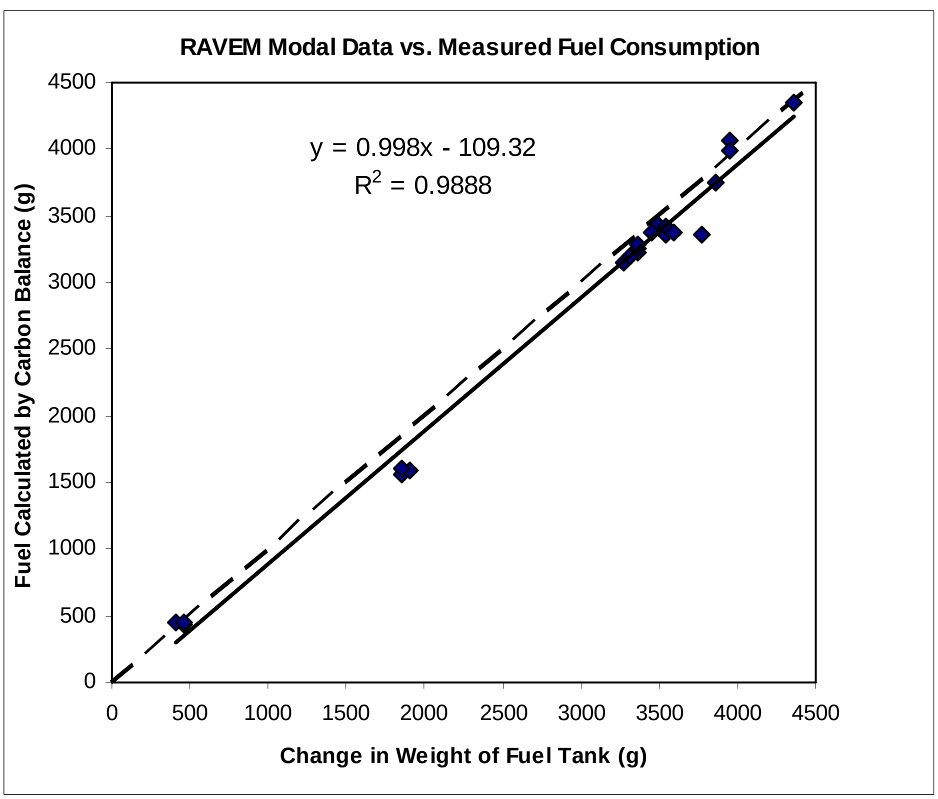

Figure 3: Fuel calculated from RAVEM modal data vs. measured fuel consumption

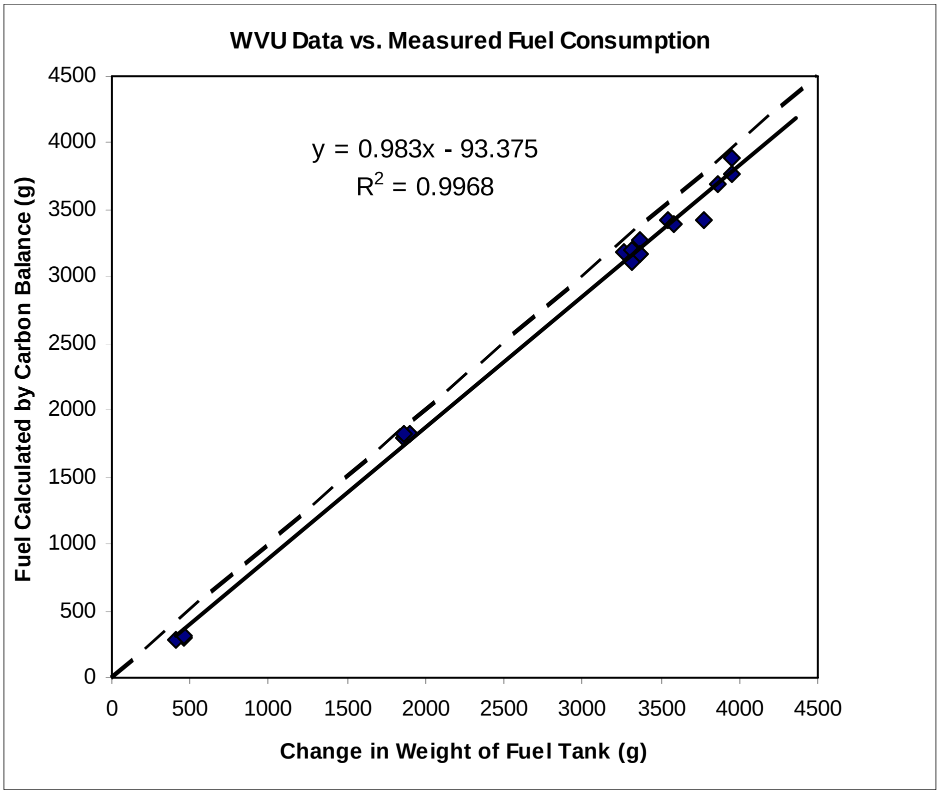

Figure 4: Fuel calculated from WVU data vs. measured fuel consumption

A comparison of the PM results from the RAVEM with those from the WVU system shows that the data correspond nearly 1-for-1 at the lower PM emission rates, but that the RAVEM data for the highest PM emission rates (those where the PM emissions were intentionally degraded) are about 20 to 25% lower than those measured by WVU. This discrepancy is well within the range of disagreement found among different heavy-duty full-flow CVS chassis dynamometer systems in round-robin testing[1]. The source of the discrepancy in this case is not immediately apparent – it could be due either to differences in dilution ratio and/or temperature, or possibly to the time-response of the RAVEM system (if the additional PM were primarily in very short-duration smoke puffs on acceleration).

In the earlier testing in Mexico City, CO emissions measured by the RAVEM correlated poorly with those measured by the WVU system. It was suggested then that this was due to differences in the two CO analyzers' response to interference from CO_2 and water vapor. The CO results in Figure 5 support this hypothesis. At low CO concentrations, the RAVEM data are generally lower than the WVU measurements, but the two agree reasonably well at higher CO concentrations.

[1] Michael L. Traver, Christopher J. Tennant, Thomas I. McDaniel, Steven S. McConnell, Brent K. Bailey, and Hector Maldonado, "Interlaboratory Cross-Check of Heavy-Duty Vehicle Chassis Dynamometers", SAE Paper No. 2002-01-2879, SAE International, Warrendale, PA 2002.

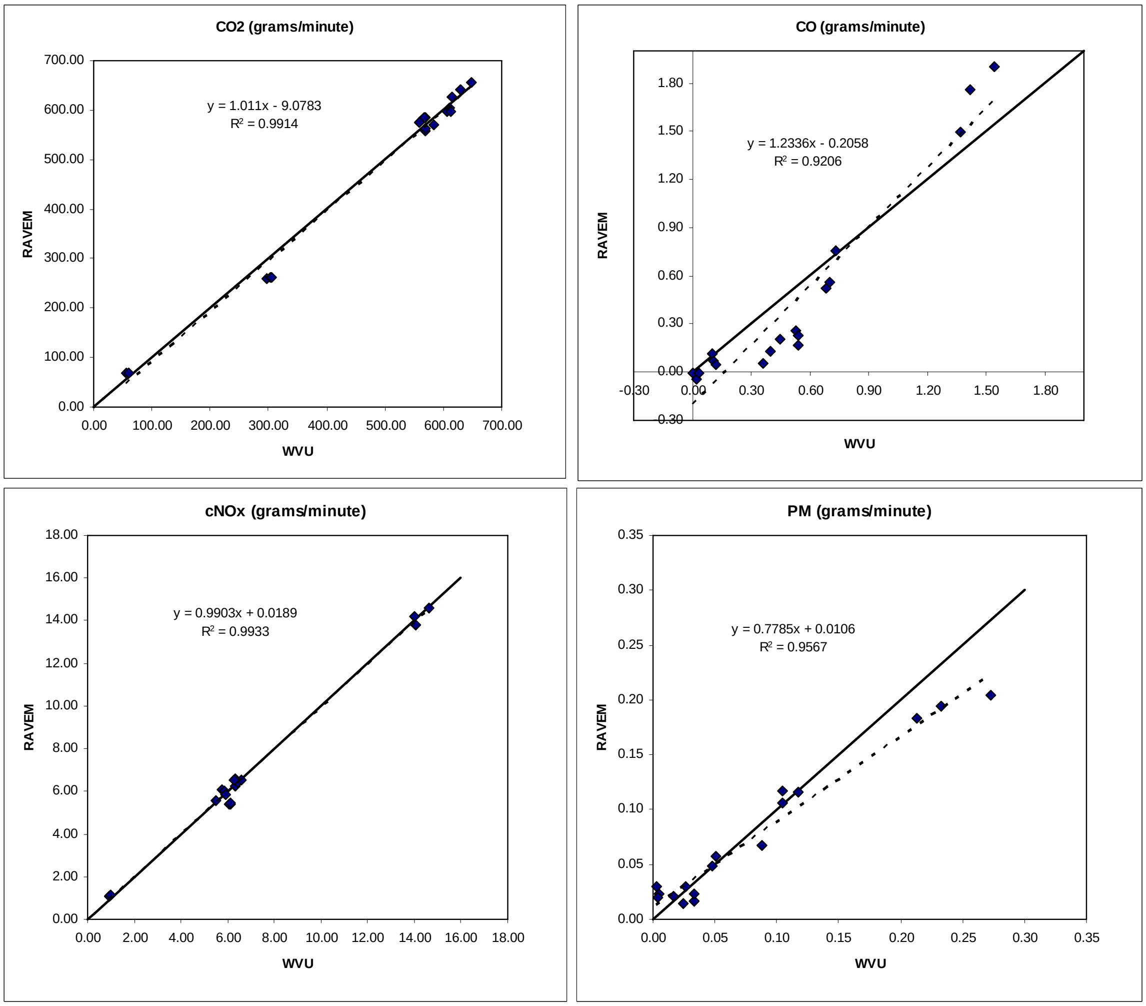

Figure 5: RAVEM bag and PM filter data vs. WVU results

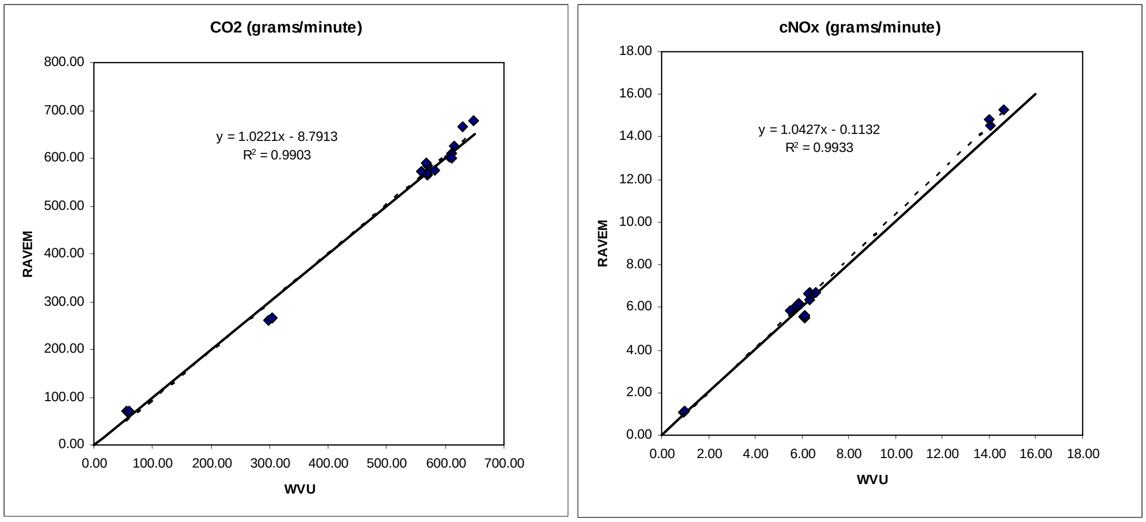

Figure 6: RAVEM modal data vs. WVU results

Conclusions

For the test vehicle and the test cycles used, emissions of NOx and CO_2 measured by the RAVEM system correlate well with those measured by the WVU Transportable Heavy Duty Emission Laboratory. In addition, fuel consumption calculated by carbon balance from the emissions measured by each system corresponds well with actual fuel consumption as measured by the change in weight of the fuel tank. PM emissions corresponded nearly 1:1 at normal PM emission rates, but the RAVEM measured about 20 to 25% lower than the WVU system when PM emissions were deliberately degraded by introducing a turbocharger pressure leak. The emission results for CO correlated poorly at low concentrations, but fairly well at higher ones. This suggests that the observed differences are due to different response to interfering species between the two CO analyzers.