EF&EE
ENGINE, FUEL, AND EMISSIONS ENGINEERING, INCORPORATED

3215 Luyung Drive
Rancho Cordova, CA 95827
ph. (916) 368-4770
fax (916) 362-2579

Results of Correlation Testing
RAVEM vs. U.C. Riverside Full-Flow CVS

Christopher Weaver, P.E.

As part of a study of portable emission measurement systems (PEMS) by the California Air Resources Board, emission tests were performed by several PEMS systems operating in parallel with the mobile emission test laboratory belonging to the Center for Emissions Research and Technology (CERT) of the University of California at Riverside's Bourne School of Engineering. The CERT mobile laboratory is a full-flow, constant-volume sampling (CVS) system designed to meet U.S. EPA requirements (40 CFR 86, subpart N) for emission measurements on heavy-duty engines and vehicles.

One of the PEMS systems participating in these tests was the Ride-Along Vehicle Emissions Measurement (RAVEM) system developed and marketed by Engine, Fuel, and Emissions Engineering, Inc. (EF&EE). Among the PEMS systems participating in the correlation test, the RAVEM system was the only one designed to measure both gaseous emissions (NOx, CO_2, and CO) and emissions of particulate matter (PM). This paper compares the results obtained by the CERT laboratory and the RAVEM system.

Test Setup

Emission tests were performed at the heavy-duty chassis dynamometer test facility of the California Air Resources Board. However, only the ARB dynamometer was used – the emission measurement systems at the ARB facility were not involved. Instead, the CERT laboratory trailer was parked next to the dynamometer test cell, as Figure 1 shows.

Figure 1: CERT laboratory trailer parked in front of ARB chassis dynamometer cell

The test truck was a Freightliner tractor equipped with a Caterpillar test engine incorporating various design features intended to meet 2007 emission standards. The truck was equipped with a catalytic converter, but not with a diesel particulate filter. Compared to typical trucks on the road, this truck exhibited low to very low emissions of NOx, PM, and CO.

The Freightliner tractor was mounted on the heavy-duty chassis dynamometer at the ARB laboratory. In order to reach the CVS system in the U.C. Riverside laboratory trailer, the truck's five-inch diameter exhaust pipe was extended by approximately 40 feet. The PEMS systems under test were installed at intervals along the extended exhaust pipe, as **Figure** 2 shows. The RAVEM's sample probe was installed in the last position, at the extreme left of **Figure** 2. This was the position closest to the CERT dilution tunnel.

Figure 2: Test truck and extended exhaust pipe with PEMS systems installed

Driving Cycles

The driving cycles used for the emission testing included two transient cycles: the U.S. EPA's Urban Dynamometer Driving Cycle (UDDS) and the highway cruise cycle averaging 50 miles per hour (50CRUISE). The UDDS is the chassis version of the U.S. Heavy-Duty Transient Test Procedure, and simulates heavy-duty vehicle operation in an urban area.

In addition to these transient driving cycles, the test sequence included four cycles involving constant speed operation at different loads, with step transitions between the load points. These were the used to assess the ability of some of the PEMS to distinguish conditions that fall with EPA's "not-to-exceed" envelope, and were therefore termed the NTE-1290, NTE-1500, NTE-1700, and NTE-Stepped.

Emission Results

The CERT and RAVEM results for the different test cycles are compared in **Table** 1. Both CERT and RAVEM data were available for seven UDDS cycles, seven 50CRUISE cycles, four NTE-STEPPED cycles, and two each of the NTE-1290, NTE-1500, and NTE-1700 cycles. No

RAVEM data were available for two NTE-STEPPED cycles; these have been omitted from the table. CERT PM data for two of the NTE cycles were invalid, and are shown as n/a.

Table 1: Emission test results

Test Name	Test Cycle	CERT Emissions g/cycle					RAVEM Emissions g/cycle			
		THC	CO	NOx	CO_2	PM	CO	NOx	CO_2	PM
200504211014	UDDS	1.30	28.2	57.8	13628	3.55	22.4	73.6	15134	3.14
200504211054	UDDS	0.48	24.0	58.8	13728	3.61	19.3	68.2	15371	3.03
200504211152	UDDS	1.18	23.3	59.2	14228	3.77	13.4	71.6	15414	3.24
200504211413	UDDS	0.57	24.9	59.4	14276	3.81	17.0	69.7	15635	3.24
200504211446	UDDS	0.73	23.7	62.0	14531	4.00	13.5	73.9	15827	3.43
200504220900	UDDS	1.36	31.5	55.9	14409	4.07	24.1	70.0	15441	3.02
200504220935	UDDS	0.93	28.1	55.6	13943	3.87	21.0	67.4	14931	2.87
	Mean	0.94	26.2	58.4	14106	3.81	18.7	70.6	15393	3.14
	Standard Deviation	0.35	3.1	2.2	345	0.19	4.2	2.5	298	0.19
	Coef. of Variation	37.7%	11.7%	3.8%	2.4%	4.9%	22.5%	3.6%	1.9%	5.9%
200504201057	50CRUISE	1.32	24.0	94.0	24581	4.30	19.9	107.4	28502	4.14
200504201233	50CRUISE	0.85	23.7	95.2	24766	4.20	17.9	110.6	28336	3.82
200504201315	50CRUISE	1.28	22.1	95.4	24507	3.98	20.1	113.3	29020	3.95
200504201405	50CRUISE	1.09	22.4	97.1	24948	4.16	13.9	107.2	27054	3.76
200504201443	50CRUISE	0.99	22.3	98.2	24709	4.29	15.4	108.0	27266	3.87
200504201514	50CRUISE	1.02	21.0	99.4	24796	4.95	11.9	115.7	27940	3.66
200504210814	50CRUISE	1.48	28.9	87.7	23989	3.42	25.5	107.9	27578	3.80
	Mean	1.15	23.5	95.3	24614	4.19	17.8	110.0	27957	3.86
	Standard Deviation	0.22	2.6	3.8	311	0.45	4.6	3.3	708	0.15
	Coef. of Variation	19.0%	11.1%	4.0%	1.3%	10.8%	25.7%	3.0%	2.5%	4.0%
200504191326	NTE_Stepped	2.45	32.0	206.7	49267	6.76	21.0	229.1	54092	4.76
200504210927	NTE_Stepped	1.61	32.1	199.0	49236	5.75	20.4	242.2	56582	4.84
200504211237	NTE_Stepped	1.72	25.8	210.6	51038	6.59	10.0	254.9	57666	5.15
200504211320	NTE_Stepped	1.77	27.5	215.3	51355	7.52	13.3	258.0	57846	6.44
	Mean	1.89	29.3	207.9	50224	6.65	16.2	246.0	56547	5.30
	Standard Deviation	0.38	3.2	6.9	1131	0.73	5.4	13.2	1729	0.78
	Coef. of Variation	20.2%	10.9%	3.3%	2.3%	10.9%	33.2%	5.4%	3.1%	14.7%
200504191000	NTE_1290	2.62	20.8	172.2	32112	4.12	12.0	193.2	35825	4.18
200504210849	NTE_1290	1.93	24.9	147.4	30227	3.44	16.6	177.9	34741	3.25
200504191046	NTE_1500	1.97	29.0	174.6	37353	4.49	21.1	200.2	42804	6.26
200504220740	NTE_1500	1.43	28.4	182.8	38092	n/a	19.7	209.0	42278	4.44
200504191234	NTE_1770	2.22	32.6	202.8	46741	7.81	25.0	227.2	52372	11.67
200504220814	NTE_1770	2.25	34.6	202.5	47532	n/a	25.3	234.1	53304	8.28

The correlation between the CO_2 emissions measured by the CERT laboratory and the RAVEM system is shown in Figure 3; while the corresponding correlation for NOx emissions is shown in Figure 4. Both correlations are very good, with R^2 values of 0.998 and 0.993, respectively. However, the slopes of both correlation lines are somewhat greater than 1.13 and 1.16, respectively, indicating that the RAVEM system was measuring 13% more CO_2 and 16% more NOx than the CERT system.

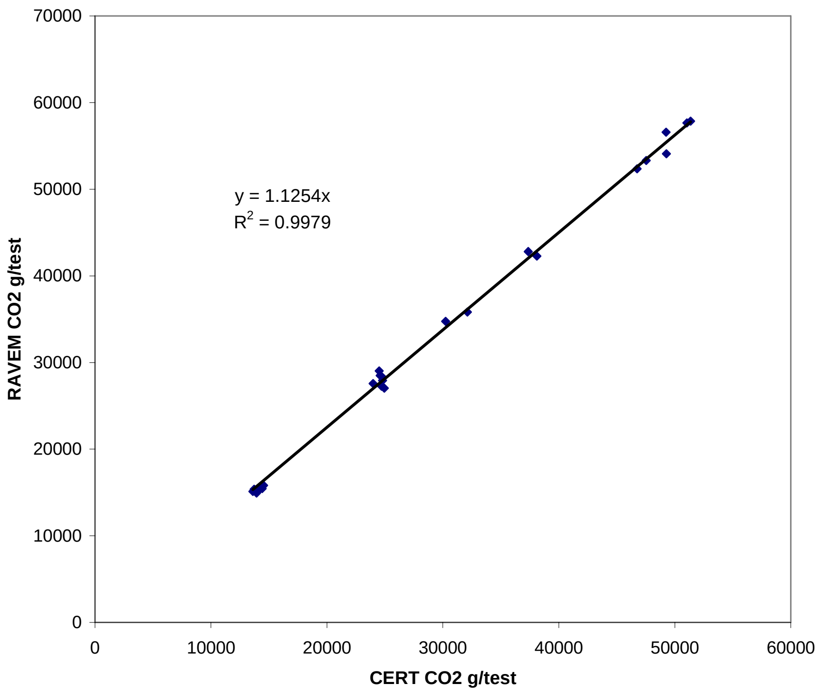

Figure 3: Correlation between RAVEM and CERT measurements of CO_2 emissions

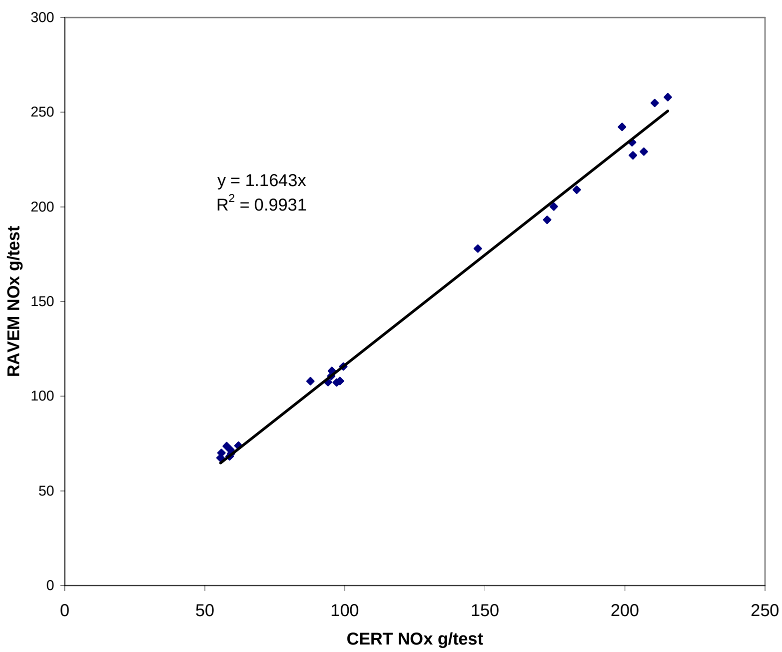

Figure 4: Correlation between RAVEM and CERT measurements of NOx emissions

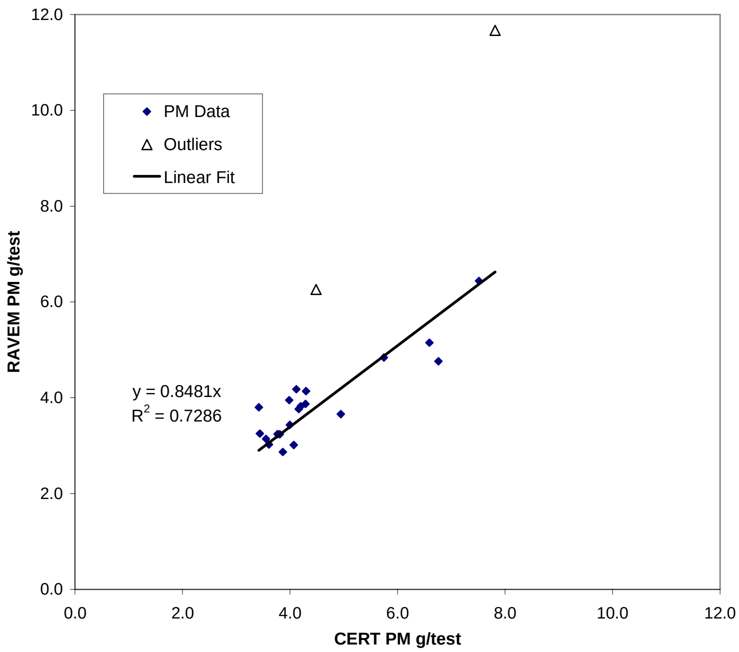

Figure 5: Correlation between RAVEM and CERT measurements of PM emissions

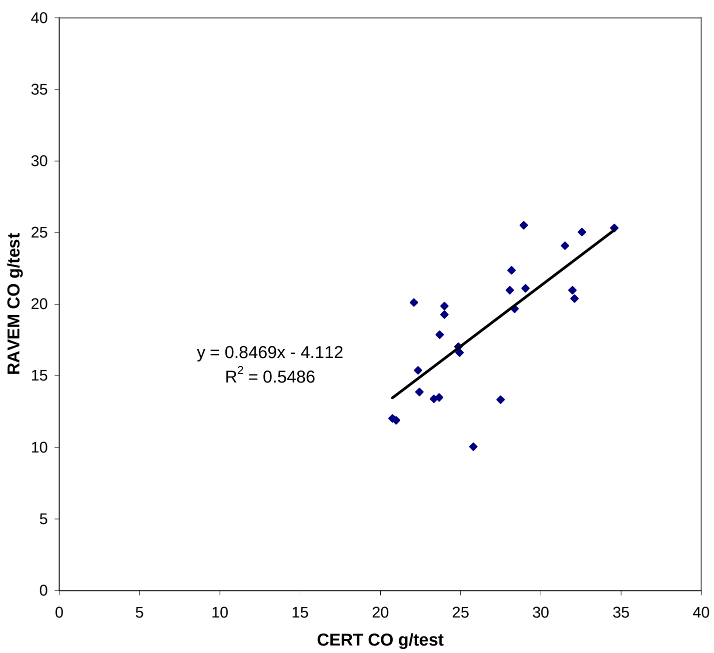

Figure 6: Correlation between RAVEM and CERT measurements of CO emissions

To assess the effects of the exhaust pressure differences due to the CERT system downstream, one 50CRUISE test was performed with the CERT system disconnected, so that the exhaust was emitted directly to the atmosphere. The RAVEM CO_2 measurements for this test were within the range of resuls for the other 50CRUISE tests performed with the CERT system connected, indicating that the presence of the CERT system had little or no effect on the RAVEM results. Although NOx measurements in this test were lower and PM measurements higher than in the other 50CRUISE tests, this is most likely due to the low ambient temperatures, since the test was carried out early in the morning.

Most of the discrepancy between RAVEM and CERT results for NOx and CO_2 can be explained by velocity stratification in the exhaust pipe. Turbulent flow in exhaust pipes normally displays a nearly homogeneous velocity distribution, except very close to the walls. However, because of the unusually long length of pipe upstream, the velocity distribution would have developed a parabolic profile, with higher velocity in the center (where the RAVEM probe was located) and lower velocity to the sides. This would have resulted in over-sampling by the RAVEM system.

In subsequent tests carried out in EF&EE's lab, the development of a parabolic velocity profile in a four inch diameter, forty foot long pipe resulted in the RAVEM system oversampling by eight percent. These tests were conducted using air, at Reynolds numbers similar to those experienced in the CERT test program. The same tests showed that the effects of velocity stratification were negligible if the RAVEM probe was positioned one-third of the diameter away from the centerline. Thus, this issue can be eliminated by changing the probe mount.

The correlation between the PM emissions measured by the RAVEM system and by the CERT laboratory is plotted in Figure 5. Inspection of this figure shows a moderately good correlation, but with two significant outliers in which the RAVEM system measured substantially higher PM emissions than the CERT laboratory. The tests that produced these outliers were the second and third tests performed in the series. These steady-state tests at 1500 and 1770 RPM were thus the first times that the exhaust pipe and sampling system were exposed to the corresponding exhaust flow rates after being assembled. The unusually high PM values measured in these tests may thus reflect the capture of pre-existing deposits or debris in the exhaust pipe or the sampling system.

Except for the two outliers, the PM results from the RAVEM system show moderate correlation with those from the CERT laboratory, with R^2 equal to 0.73. The strength of this correlation is affected by the limited range of PM test results, and by test-to-test variability of about 10% in each of the two sets of measurements. This percentage variability is largely attributable to the very low level of PM emissions from this truck, which were equivalent to approximately 0.04 to 0.06 grams per BHP-hr. At such low PM levels, the normal level of uncertainty in the filter weighing has a substantial effect on the results.

The slope of the correlation line for the PM measurements is 0.85 – so that the PM emissions measured by the RAVEM were – on average – about 15% less than those measured by the CERT laboratory. Combined with the 13-to-15% over-measurement of CO_2 and NOx emissions, these results show that – relative to the gaseous emission measurements – the RAVEM system's PM measurements average about 28 to 30% lower than those of the CERT laboratory. This is consistent with the results of earlier correlation tests, and well within the normal range of lab-to-lab variation for PM measurements[1].

---

[1] M.L. Traver et. al., "Interlaboratory Cross Check of Heavy-Duty Vehicle Chassis Dynamometer", SAE Paper No. 2002-01-2879.

The likely source of the difference in PM measurements is a difference in the retention of water and volatile components of the PM. This could be due to differences in the overall dilution ratio, filter face velocity, filter retention time before weighing, and/or the filter material.

CO emissions measured by the RAVEM and CERT systems are compared in Figure 6. CO emissions from modern diesel engines tend to be very low. The test truck was also equipped with a catalytic converter, giving even lower CO emissions. The CO measurements were therefore close to the limits of detection for the analyzers, resulting in the significant scatter visible in the graph. At these very low CO concentrations, interference by water vapor and CO_2 can have a large percentage effect on the CO measurements. Differences in response to these interfering species probably account for the offset in the best-fit line shown in Figure 6.

Conclusions

NOx and CO_2 emissions measured by the RAVEM system showed close correlation with those measured by the U.C. Riverside CERT laboratory, but the slopes of the correlation lines were 1.16 and 1.13, respectively. The discrepancy in slope is mostly due to velocity stratification in the very long exhaust pipe used. This effect can be eliminated by mounting the probe one-third diameter away from the centerline of the exhaust pipe, rather on it.

PM emissions measured by the RAVEM system showed moderate correlation with those measured by the CERT laboratory, but the slope of the correlation line was 0.85. The observed correlation was about as good as could be expected, given the limits of precision of filter weighing and the very low level of PM emissions from the test vehicle. CO emissions were close to detection limits, and show considerable scatter.