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Reproducibility and Accuracy of On-Board Emission Measurements Using the RAVEM™ System

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ABSTRACT

Portable systems capable of measuring mass exhaust emissions while riding on-board vehicles and mobile equipment are relatively new. Their advantages include lower measurement costs, the ability to measure emissions under realistic operating conditions (including conditions that are difficult to simulate in the laboratory), the ability to measure emissions where no traditional laboratory is available, and applicability to a broader range of engines and vehicles than those addressed by traditional laboratory methods (e.g. construction machinery). However, on-board methods have not yet been fully accepted in the air quality community. This is due in part to concerns over their reproducibility and accuracy, and the adequacy of the corresponding quality assurance and quality control measures. This paper draws on four years of experience with on-board emission measurements using the "Ride-Along Vehicle Emission Measurement" (RAVEM) system in vehicles ranging from diesel and natural gas trucks to diesel ferryboats and locomotives. Quality assurance methods such as carbon-balance and CO_2 recovery checks of emission measurement accuracy have been developed, together with driving techniques to generate reproducible on-road emissions data. Results are presented showing repeatability (based on the standard deviation of repeated emission measurements over the same driving route) generally within 6% for CO_2 and NOx (in the absence of NOx aftertreatment systems), and within 10% for PM. Comparison of fuel consumption calculated by carbon balance to the mass fuel consumption determined by weighing the fuel tank shows agreement generally within 1 to 4%.

INTRODUCTION

Portable systems capable of on-board measurement of mass exhaust emissions from vehicles and mobile equipment are relatively new, and offer some important advantages compared to traditional laboratory methods. Depending on the application and the measurement system, these advantages may include:

- Lower measurement costs;
- The ability to measure emissions under realistic operating conditions (including conditions, such as trash collection or earthmoving, that are difficult to simulate in the laboratory);
- The ability to measure emissions where no traditional emission laboratory is available;
- Applicability to a broader range of engines and vehicles than those addressed by traditional laboratory methods (for example, earthmoving equipment, boats, and locomotives).

Corresponding disadvantages of on-board methods include a lesser degree of control over environmental conditions and operating cycles than in traditional laboratory methods, and the presence of additional sources of measurement error.

Another disadvantage of on-board measurement methods at present is that these methods have not yet been fully accepted by the air quality regulatory community. This is due in part to concerns over their reproducibility and accuracy, and over the adequacy of the corresponding methods for quality assurance and quality control.

The "Ride Along Vehicle Emission Measurement" (RAVEM) system was presented in a previous paper (1). This system was among the first on-board emission measurement systems developed, and remains one of very few that can accurately measure emissions of particulate matter (PM). During the last three years, the authors have applied the RAVEM system to measure pollutant emissions from a wide variety of mobile sources, ranging from natural gas garbage trucks in Mexico City (2) to diesel ferryboats on San Francisco Bay (3). It has also been applied to the evaluation of emission control systems including selective catalytic reduction (SCR), diesel particulate filters (DPF), diesel oxidation catalysts (DOC) and emulsion fuels.

In the course of this work, we have implemented a number of technical improvements, have expanded the range of pollutants that can be measured, and have developed quality assurance methods and procedures to assure the accuracy and reproducibility of the results obtained. Quality assurance methods include carbon-balance and CO_2 recovery checks of emission measurement accuracy, as well as driving techniques to generate reproducible on-road emissions data.

RAVEM SYSTEM OVERVIEW

As reference 1 explains in more detail, the RAVEM system is based on proportional *partial-flow* constant volume sampling (CVS). The key advantage of the CVS principle for vehicle emission measurements is that the pollutant *concentration* in the 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. 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 be determined by integrating the concentration measurement alone; the CVS mass flow rate enters only as a constant multiplier.

Conventional emission laboratory methods defined by the U.S. EPA (4) and the International Standards Organization (5) 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 a portion of the total exhaust flow, using an isokinetic proportional sampling system (6). This system comprises a set of static pressure taps inside and outside the sampling probe, a sensitive differential pressure transducer, and a closed-loop control system that opens and closes a throttle to increase or decrease the pressure in the dilution tunnel, thus decreasing or increasing the velocity of the exhaust sample flowing inside the probe. This continues until the static pressure inside the probe is equal to that in the remainder of the exhaust stream flowing outside. Neglecting gas friction in the probe, this occurs when the exhaust gas velocities inside and outside the probe are equal. The fraction of the exhaust flow passing through the probe is then given by a simple geometric constant – that of the cross-sectional area of the probe channel to that of the exhaust pipe.

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. The total weight of the RAVEM system is approximately 120 kg (excluding calibration gas cylinders, which can be left off-board), and the total power demand is approximately 600 watts. This power can generally be provided by the vehicle's electrical system.

A schematic diagram of the RAVEM system is shown in Figure 1. Except for the isokinetic sampling system at the top of the figure, this diagram closely resembles a conventional single-dilution CVS emission measurement system.

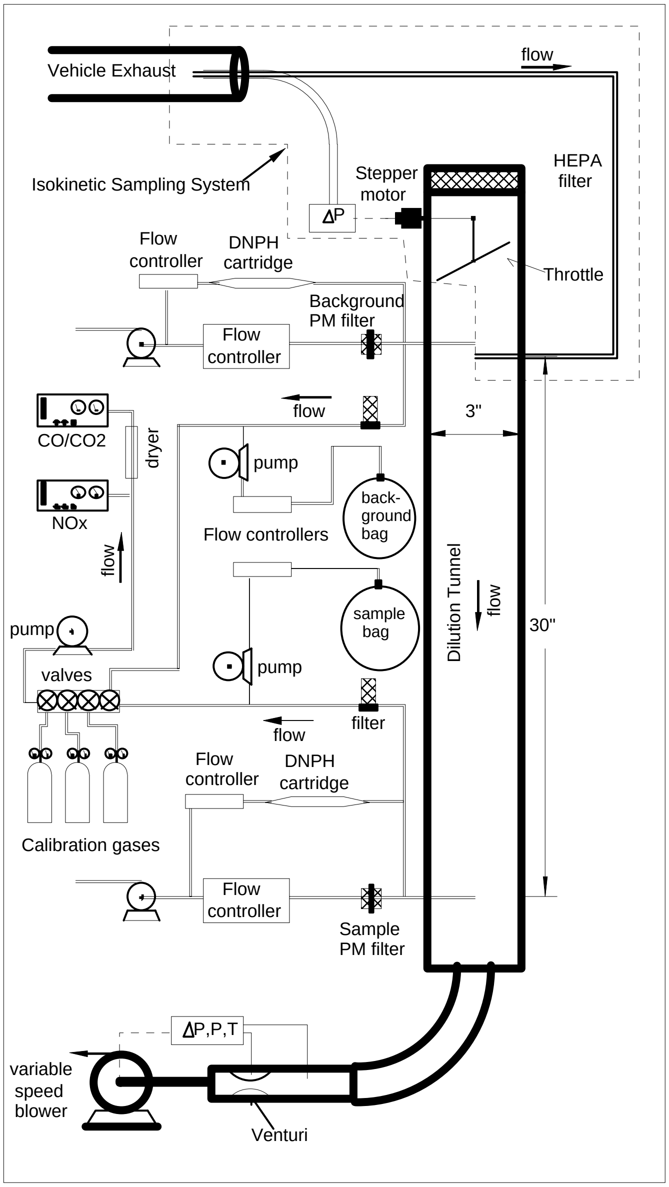

Figure 1: Schematic diagram of the RAVEM system

In CVS sampling for particulate matter, integration is accomplished by passing dilute exhaust mixture through a pre-weighed filter at a constant 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. For gases, integration can be accomplished either by physical means – collecting the sample in a bag at a constant rate, then measuring the average pollutant concentration in the bag – or by electronic integration of the instantaneous pollutant concentrations. The RAVEM system uses both approaches: measuring and recording second-by-second pollutant mass flow rates as well as collecting integrated samples of the dilute exhaust mixture and the dilution air in Tedlar® bags.

The collection of integrated bag samples makes possible the application of analytical techniques that would not otherwise be practical in portable applications. For example, Fourier transform infrared (FTIR) methods have been applied to these samples to quantify N_2O and ammonia emissions; and gas chromatographic analyses have been used to quantify methane and non-methane hydrocarbons, as well as individual hydrocarbon species of interest such as benzene and toluene (3).

As Figure 1 indicates, the design of the RAVEM system also allows the collection of integrated cartridge samples for subsequent laboratory analysis. For example, di-nitro phenyl hydrazine (DNPH) cartridges have been used to quantify emissions of formaldehyde, acetaldehyde, and other carbonyls.

CORRELATION TEST RESULTS

Because the RAVEM system extracts less than one percent of the exhaust flow, it can easily be run in parallel with a conventional full-flow CVS system. Validation tests were carried out on the second-generation "breadboard" prototype RAVEM system, measuring in parallel with an EPA recognized chassis dynamometer emission laboratory: California Truck Testing Systems (CaTTS) located in Richmond, California.

The validation test program was conducted jointly with the California Air Resources Board during March and April, 2001. The program involved a total of 33 emission tests on two trucks. One was a highway maintenance truck equipped with a Navistar DT466 "green diesel" engine and a continuously regenerating diesel particulate trap. The other was a tractor equipped with a Cummins 14-liter, 350 horsepower engine. The results of the test program are summarized in Figures 2 through 4. As these figures show, the RAVEM results for CO_2, NOx, and PM correlated closely with the results from CaTTS. CO results showed poor correlation between the two systems. This was attributed to the very low CO concentrations found, which meant that differences in the water interference response between the analyzers were large compared to the measured CO concentrations.

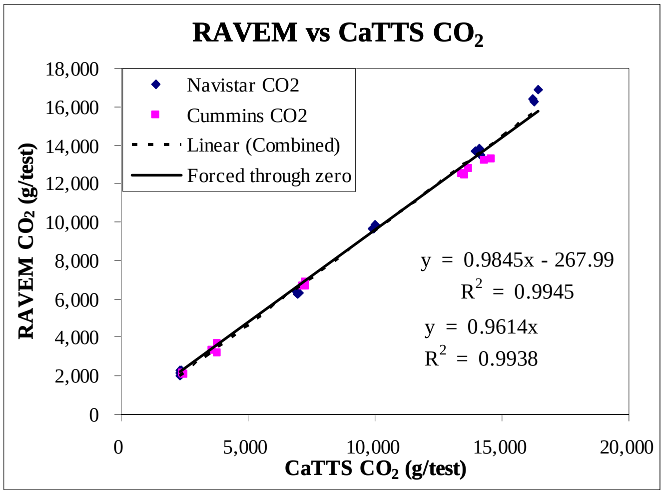

Figure 2: NOx measured by the RAVEM system vs. results from a conventional emission laboratory

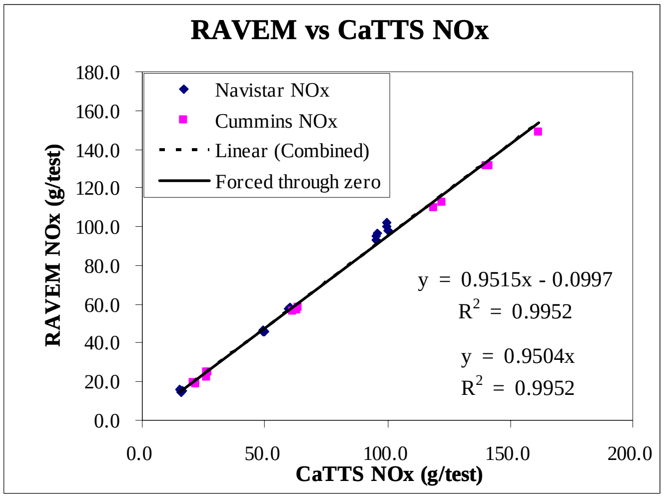

Figure 3: CO_2 measured by the RAVEM system vs. results from a conventional emission laboratory.

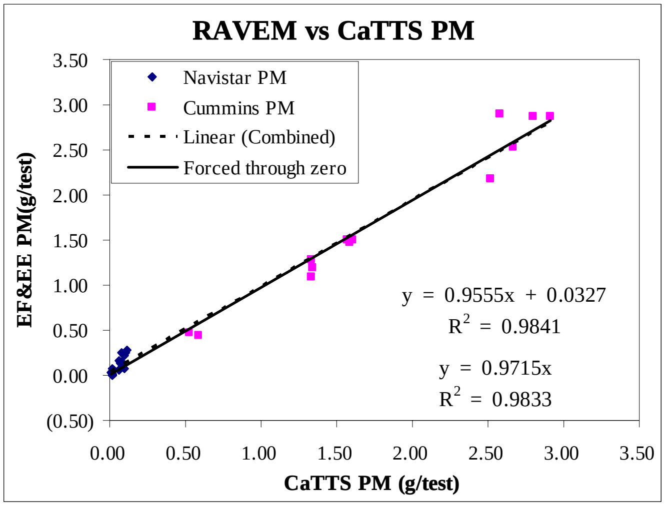

Figure 4: PM measured by the RAVEM system vs. results from a conventional emission laboratory.

SOURCES OF ERROR AND COUNTERMEASURES

Experience with the RAVEM system has shown that the principal contributor to error in the emission results is inaccuracy in determining the CVS flow rate. Any error in this value results in a corresponding error in all of the pollutant mass flow measurements. Critical flow venturis are highly accurate and stable regulators of CVS flow, but the pumping power required to achieve critical flow makes them impractical for portable systems. Instead, the RAVEM uses a variable-speed blower with a closed-loop control system designed to maintain a constant (user selectable) molar flow rate between 400 and 1100 standard liters per minute.

Leaks in the tubing and valves that conduct the gas sample to the analyzers are another potential source of error. A leak check on the system as far as the Tedlar bags is conducted each time a bag is emptied. Experience has shown that the Tedlar bags used are the weakest points in the system, tending to fail at the tubing connection point. It has been found prudent to carry a number of spare bags when going into the field.

The integrity of the entire CVS system and gas analysis system is checked by means of a CO_2 recovery test. With the CVS sampling system running, pure CO_2 from a small high-pressure cylinder is injected into the sample probe for about 30 minutes at a rate that gives a CO_2 concentration reading of about 80% of analyzer full scale in the dilute sample. CO_2 concentrations in the dilute exhaust are measured second-by-second during the test, and checked afterward against the integrated bag sample collected at the same time. The CO_2 cylinder is weighed before and after the test, and the change in weight (typically 100 to 150 grams) is compared to the total mass of CO_2 calculated from the CVS measurements. The CO_2 emissions determined from the bag sample concentration, the integrated modal concentrations, and the change in mass of the CO_2 cylinder should all agree within two to three percent.

Errors in emission results due to the RAVEM's isokinetic sampling system have been found to be uncommon, except at very low exhaust velocities where the delta-pressure signal is too low to maintain stable control. When errors are found, they are generally due to leaks or blockage of the pressure lines connecting the static pressure taps in the probe to the delta-P sensor. Since the delta-pressure lines often exhibit a common-mode pressure above or below atmospheric, a leak can significantly distort the delta-P signal. To check for these, as well as for calibration of the sensor itself, the authors have designed and built a special delta-pressure calibration system, capable of supplying air at low differential pressures (0.5 inches water gage, full-scale) with a common-mode pressure of 1-2 inches w.g.

Another source of potential error in the isokinetic sampling system is inhomogeneity in the distribution of flow velocities in the exhaust pipe and/or misalignment of the probe axis with the local flow velocity. For example, recent tests where the probe inlet was mistakenly located at the exit from a 90 degree elbow gave results that were consistently 9-10% lower than a conventional CVS system measuring in parallel. This type of error can be prevented by providing a section of straight pipe upstream – preferably least 10 diameters in length. Where the exhaust pipe configuration on the vehicle does not allow this, an exhaust pipe extension can be used.

Carbon balance checks are an extremely important QA measure where they are feasible. By inserting three-way valves into the engine fuel supply and return lines, it is possible to draw the fuel consumed during a test from a separate, detachable fuel tank. This fuel tank is weighed before and after the emission test, and the result is compared to the mass fuel consumption corresponding to the sum of the carbon emissions (CO_2 + CO) measured by the RAVEM system. This checks the accuracy of the entire sampling system, from the isokinetic sampler through the CVS and the CO/CO_2 gas analyzer system. The results of the two measures normally agree within three to four percent.

Carbon balance checks do not directly validate the measurements of NOx, PM, or other pollutants other than CO_2. Since these pollutants are sampled through the same extraction port as the CO_2, however, these checks do validate the performance of the sampling system as far as the "Y" connecting the sample line to the different analyzers and collection mechanism. In addition, the correlation test results show very close agreement between the fuel-specific NOx and PM values measured by the RAVEM system and by the CaTTS laboratory. As Figures 5 and 6 show, the slope of the best-fit line in each case is nearly 1:1.

The NOx, and CO_2 samples pass through the same sample pump, and the branch of the "Y" going to the NOx analyzer is under positive internal pressure; so that there is little chance that a leak could affect the NOx reading independent of the CO_2 reading. Errors in the calibration of the NOx analyzer itself are prevented by adherence to EPA protocols for analyzer calibration.

The dilute exhaust samples for PM and carbonyl determination are taken through the same dilution tunnel probe as the CO/CO_2/NOx sample, but are subsequently drawn through separate filters (for PM) or DNPH cartridges (for carbonyls), as shown in Figure 1. In each case, flow is controlled by electronic flow controllers. Any leak in this part of the system could affect the corresponding results. Periodic leak checks are therefore employed to guard against such leakage.

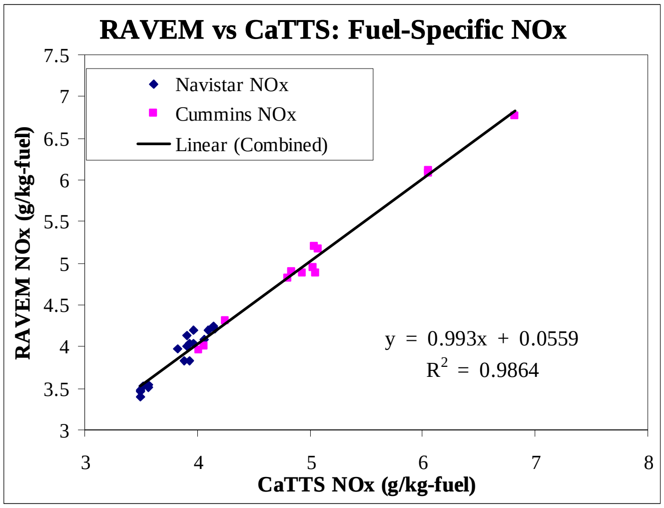

Figure 5: Fuel-specific NOx emissions from RAVEM data vs. results from a conventional emission laboratory.

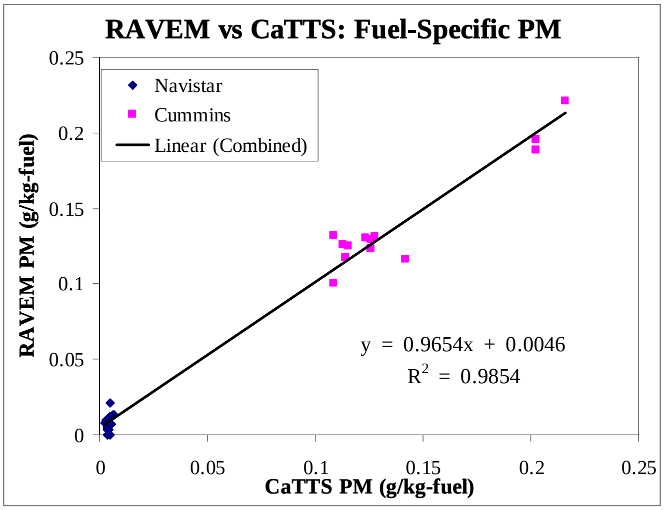

Figure 6: Fuel-specific PM emissions from RAVEM data vs. results from a conventional emission laboratory.

EXAMPLE: SCR EFFECTIVENESS IN A CLASS 8 TRACTOR-TRAILER TRUCK

Emission tests were conducted to assess the effectiveness of a prototype selective catalytic reduction (SCR) system in reducing emissions from a diesel tractor-trailer. The emission tests also examined the effect of the low-NOx recalibration or "reflash" developed by the engine manufacturer under the heavy-duty diesel consent decree of 1998. That recalibration is intended to reduce the impacts of injection timing control strategies that have been characterized as "defeat devices" by the U.S. EPA and the California Air Resources Board.

The test truck with the RAVEM system installed is shown in Figure 7. To simulate normal lading, the equipment trailer was ballasted with a second truck, giving a gross combined vehicle weight of approximately 62,500 pounds. Emissions were measured over the Sunrise Freeway Route, a defined driving route that includes a mix of freeway and non-freeway driving typical of heavy-duty truck operation in urban areas. All of the driving was over public roads, but test times were selected to avoid periods of high congestion. The average load factor over the test route was approximately 32%, which compares well with the 35% load factor in the U.S. heavy-duty transient test cycle.

The emission test results are summarized in Table 1. The repeatability ranged from good to excellent, with coefficients of variability (standard deviation divided by the mean) generally less than 6%, and often less than 3%. CO emissions exhibited greater variability -- a result of the extremely low CO concentrations, which approached the limits of accuracy of the on-board gas analyzer. Integrated real-time NOx and CO_2 emissions also agree well with the tedlar bag data. The repeatability appeared to improve during the test program as the driver gained familiarity with the vehicle and the test route.

Figure 7: Class 8 tractor-trailer with RAVEM system installed

Carbon-balance checks were employed as a quality-assurance measure during these tests. The actual mass of fuel consumed during each test was measured by weighing and reweighing a detachable fuel tank using an electronic laboratory balance. The "carbon balance" columns in the table show the percentage difference between the mass fuel consumption determined in this way and that calculated from the measured CO_2 and CO emissions. As the table shows, these two independent fuel consumption measures agree within one to three percent, giving confidence in the accuracy of the emission results.

EXAMPLE: SCREENING OF LOW-EMISSION FUEL FORMULATIONS

The RAVEM system was used in a medium-duty pickup truck equipped with a 5.9 liter turbocharged diesel engine for screening-level evaluation of a potential reduced-emission diesel fuel formulation. The test compared emissions using CARB diesel to those produced using biodiesel and a proprietary low-emission diesel fuel formulation. Testing was conducted over the Sunrise Freeway route, with an extension to include additional stop-and-go driving. The pickup's power-to-weight ratio is much higher than a typical heavy duty vehicle. Thus, to achieve engine load factors typical of urban truck operation, the vehicle was hitched to a heavy trailer.

The test results are summarized in Table 2. Repeatability is generally good to excellent, with coefficients of variation for NOx and CO_2 in the range of two percent. PM repeatability was also good for biodiesel and CARB diesel, but results with the experimental fuel showed greater variation. The carbon balance results reflect the difference between the mass fuel consumption as calculated from the CO_2 + CO emissions and the fuel composition, and that measured directly using the detachable fuel tank and an electronic balance. Again, these two independent measures of fuel consumption agree within 0.2 to 2.4 percent.

CONCLUSION

The "ride along vehicle emission measurement" (RAVEM) system was among the first portable systems capable of measuring mass pollutant emissions on-board a moving vehicle, and is one of very few such systems shown to be capable of accurately measuring emissions of particulate matter (PM). During the last three years, it has been applied to a wide variety of emission measurements. The range of pollutants that can be measured has been expanded, and now includes carbonyls, VOC, air toxics, N_2O, and ammonia as well as NOx, CO, CO_2, and PM. Quality assurance methods and procedures have been developed to assure the accuracy and reproducibility of the emission measurements. These include carbon-balance and CO_2 recovery checks of emission measurement accuracy, as well as driving techniques to generate reproducible on-road emissions data. With careful planning, repeatability levels for diesel vehicles (based on the standard deviation of repeated emission measurements over the same driving route) can generally be brought within 6% for CO_2 and NOx (in the absence of NOx aftertreatment systems), and within 10% for PM. Comparison of fuel consumption calculated by carbon balance to the mass fuel consumption determined by weighing the fuel tank shows agreement generally within one to four percent.

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Table 1: On-Road RAVEM emission results for a tractor trailer -- effects of SCR and low-NOx recalibration

	Bag Emissions Data (g/mi)				Filter	Integ. Realtime Data (g/mi)			Measured	Carbon Balance	
Test				Calculated	PM			Calculated	Fuel Cons	(Calc vs. Meas Fuel)	
ID	CO_2	NOx	CO	Fuel Cons	g/mi	CO_2	NOx	Fuel Cons	g/mi	Bag	Integ
WITH RECS -- BEFORE REFLASHING											
Cold Start	2,551	11.5	4.10	805.0	#N/A	2,531	12.1	798.4	815.9	-1.3%	-2.1%
Warm Start 1	2,444	9.0	1.65	770.2	0.281	2,416	9.1	764.6	778.7	-1.1%	-1.8%
Warm Start 2	2,195	8.5	2.22	691.9	0.255	2,185	8.6	685.9	720.9	-4.0%	-4.9%
Warm Start 3	2,243	10.4	2.92	707.6	0.280	2,194	10.7	692.1	718.4	-1.5%	-3.7%
Average Warm Start	2,294	9.3	2.26	723.2	0.272	2,265	9.4	714.2	739.3	-2.2%	-3.4%
Std Deviation	132	1.0	0.64	41.4	0.015	131	1.1	43.8	34.1		
Coeff of Variation	5.8%	10.4%	28.1%	5.7%	5.4%	5.8%	11.5%	6.1%	4.6%		
WITHOUT RECS -- BEFORE REFLASHING											
Warm Start 1	2,312	22.5	#N/A	727.5	0.396	2,260	22.9	713.2	723.4	0.6%	-1.4%
Warm Start 2	2,420	23.5	1.95	762.7	0.451	2,406	23.9	756.4	762.1	0.1%	-0.8%
Average	2,366	23.0	1.95	745.1	0.424	2,333	23.4	734.8	742.8	0.3%	-0.8%
Std Deviation	76	0.7	#N/A	24.9	0.039	103	0.7	30.5	27.4		
Coeff of Variation	3.2%	3.0%	#N/A	3.3%	9.2%	4.4%	3.0%	4.2%	3.7%		
WITHOUT RECS -- AFTER REFLASHING											
Cold Start	2,595	21.7	2.26	817.9	#N/A	2,509	22.8	791.6	824.0	-0.7%	-3.9%
Warm Start 1	2,352	18.7	2.17	741.3	0.441	2,345	19.4	739.4	732.6	1.2%	0.9%
Warm Start 2	2,440	21.2	2.21	769.2	0.451	2,414	21.4	760.5	772.0	-0.4%	-1.5%
Warm Start 3	2,480	21.0	1.58	781.3	0.469	2,456	21.4	774.2	774.4	0.9%	0.0%
Average Warm Start	2,424	20.3	1.99	763.9	0.454	2,405	20.7	758.0	759.6	0.6%	-0.2%
Std Deviation	66	1.4	0.35	20.5	0.014	56	1.2	17.5	23.5		
Coeff of Variation	2.7%	6.9%	17.7%	2.7%	3.2%	2.3%	5.6%	2.3%	3.1%		
WITH RECS -- AFTER REFLASHING											
Warm Start 1	2,456	8.8	3.48	774.8	0.298	2,426	8.7	765.1	777.2	-0.3%	-1.6%
Warm Start 2	2,335	6.6	2.98	736.5	0.304	2,343	6.7	739.3	740.5	-0.5%	-0.2%
Warm Start 3	2,363	6.8	2.75	745.1	0.297	2,162	6.9	682.2	710.4	4.9%	-4.0%
Average	2,385	7.4	3.07	752.1	0.300	2,310	7.5	728.9	742.7	1.3%	-1.9%
Std Deviation	63	1.2	0.38	20.1	0.004	135	1.1	42.4	21.3		
Coeff of Variation	2.7%	16.7%	12.3%	2.7%	1.2%	5.8%	14.9%	5.8%	2.9%		
PERCENTAGE CHANGE DUE TO EMISSION CONTROLS											
RECS - Unflashed	-3.0%	-59.5%	16.3%	-2.9%	-35.8%	-2.9%	-59.8%	-2.8%	-0.5%		
Effect of Reflashing	2.4%	-11.7%	2.2%	2.5%	7.1%	3.1%	-11.5%	3.2%	2.3%		
RECS - Reflashed	-1.6%	-63.4%	54.4%	-1.5%	-34.0%	-3.9%	-64.0%	-3.8%	-2.2%		
Combined RECS+Reflash	0.8%	-67.7%	57.8%	0.9%	-29.3%	-1.0%	-68.2%	-0.8%	0.0%		

Table 2: On-road RAVEM emission results from a diesel medium-duty vehicle using different fuels

Test ID	Bag Emissions Data (g/mi)					Integrated Realtime Data (g/mi)				Carbon Balance (Calc vs. Meas Fuel)	
	CO_2	NOx	CO	Calculated Fuel Cons	PM g/mi	CO_2	NOx	Calculated Fuel Cons	Fuel Cons g/mi	Bag	Integ
CARB DIESEL FUEL											
Test 1	793	7.7	0.70	250.1	0.151	812	7.9	256.0	250.2	-0.1%	2.3%
Test 2	819	8.0	0.57	257.9	0.146	825	8.0	260.2	250.7	2.9%	3.8%
Test 3	794	7.7	0.78	250.3	0.145	795	7.8	250.7	250.4	-0.1%	0.1%
Test 4	812	7.6	0.56	255.9	0.167	830	7.7	261.7	261.2	-2.0%	0.2%
Average	804	7.8	0.65	253.5	0.152	815	7.8	257.2	253.1	0.2%	1.6%
Std. Deviation	13	0.2	0.11	4.0	0.010	16	0.1	4.9	5.4		
Coeff of Variation	1.6%	2.2%	16.4%	1.6%	6.7%	1.9%	1.5%	1.9%	2.1%		
EXPERIMENTAL FUEL "A"											
Test 1	768	6.5	0.73	287.6	0.106	788	6.6	295.0	289.9	-0.8%	1.8%
Test 2	760	6.5	0.84	284.4	0.135	770	6.4	288.6	282.0	0.8%	2.3%
Test 3	789	6.7	0.80	295.4	0.136	819	6.8	306.9	300.4	-1.7%	2.2%
Test 4	793	6.5	0.83	296.8	0.158	814	6.5	304.8	295.0	0.6%	3.3%
Average	777	6.5	0.80	291.1	0.134	798	6.6	298.9	291.9	-0.3%	2.4%
Std. Deviation	16	0.1	0.05	6.0	0.021	23	0.2	8.6	7.8		
Coeff of Variation	2.1%	1.4%	6.2%	2.1%	15.7%	2.9%	2.5%	2.9%	2.7%		
BIODIESEL (B100)											
Test 1	802	8.3	0.64	283.8	0.146	809	8.5	286.4	289.3	-1.9%	-1.0%
Test 2	820	8.2	0.85	290.3	0.159	812	8.3	287.5	286.3	1.4%	0.4%
Average	811	8.3	0.75	287.0	0.152	810	8.4	286.9	287.8		
Std. Deviation	13	0.1	0.14	4.6	0.010	2	0.1	0.7	2.1		
Coeff of Variation	1.6%	1.1%	19.3%	1.6%	6.3%	0.3%	1.6%	0.3%	0.7%		