Remote Measurements of On-Road Emissions from Heavy-Duty Diesel Vehicles in California; Year 3, 2010

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Executive Summary

The University of Denver conducted two five-day remote sensing studies on heavy-duty diesel vehicles (HDDVs) at two sites in the Los Angeles Basin area of California in April/May of 2010. Two remote sensing instruments were used to measure emissions in a single lane from the elevated plumes of HDDV truck exhausts: RSD 4600 made by ESP and FEAT 3002 equipped with dual UV spectrometers from the University of Denver. These remote sensors measure the ratios of pollutants to carbon dioxide in vehicle exhaust. From these ratios, we calculate the mass emissions for each pollutant per mass or volume of fuel. The system from the University of Denver was also configured to determine the speed and acceleration of the vehicle, and was accompanied by a video system to record the license plate of the vehicle. The motivation for the study is implementation of National new vehicle emission standards and California retrofit and replacement standards for these trucks. This report summarizes the third year's activities in a five-year measurement program to monitor HDDV fleet and emission changes and compliance with the standards.

Five days of field work at each of two sites between April 26 and May 7, 2010 were conducted, resulting in 3,855 HDDV emission measurements. The sites chosen were Peralta Weigh Station on California State Route 91 (the Riverside Freeway) in Anaheim near the Weir Canyon Road exit and a truck exit on Water St. at the Port of Los Angeles in San Pedro. The Peralta Weigh station site was previously used in 1997 to collect measurements and adds a historical perspective to those measurements. Emissions analysis was performed on measurements that recorded a valid emission flag on the FEAT instrument for all gas species not including opacity. The heavy-duty fleet observed at Peralta was about five years older than the vehicles in use at the Port location (2002 vs. 2007.9) and was measured at higher operating speeds than the vehicles in use at the Port location (~13 mph compared with ~5 mph). The fleet age at the Port has changed significantly between our sampling campaigns in 2009 and 2010, averaging about four years newer (2003.5 in 2009 vs. 2007.9 in 2010). A database for each site was compiled at Peralta and the Port, respectively, for which the states of Arizona, California, Illinois, Oklahoma, Texas and Washington provided make and model year information. This database, as well as any previous data our group has obtained for HDDV's can be found at www.feat.biochem.du.edu.

Remote sensing measurements of HDDV exhaust at the Peralta site between 1997 and 2010 show large reductions in carbon monoxide (CO, 29%), hydrocarbons (HC, 16%), and nitric oxide (NO, 23%). License plates were not read and matched during the 1997 measurements so we are unable to comment with any certainty on how fleet changes during the past eleven years may have contributed to these readings. Nitrogen oxides (NO_x) emissions for the 2010 measurements were 8% lower at the Port of Los Angeles when compared with the Peralta location. This is a significant change from measurements made in 2008 and 2009 where the NO_x emissions were larger at the Port for both years of measurements. In large part, the NO_x emissions reductions at the Port in 2010 are due to the Clean Air Action Plan (CAAP) which has banned all pre-1989 model year trucks starting in October 2008. The next phase of the CAAP started in January

2010 which bans all pre-1994 model year trucks and non-retrofitted model years 1994-2003 that do not meet the 2007 EPA standards. This phase is present in the 2010 measurements that show a 23% NO_x reduction, compared to measurements made in 2009.

At Peralta 110 out-of-state trucks were plate matched and were compared to California plated trucks. The out-of-state trucks were 3.2 model years newer than the California fleet, and their average measured emissions were lower than the California fleet (see Table 5). We also observed that gNO_x/kg emissions are decreasing rapidly with newer model year vehicles but apparently have yet to reach the levels that are dictated in the 2010 National requirements. Particulate matter (PM) emissions, as measured in the infrared and ultraviolet wavelength regions, are also decreasing with the newer models. The drop in PM correlates with increases in the NO_2/NO_x ratio.

Average ammonia emissions have increased at the Port since 2008 when natural gas burning engines were introduced. This observation arises from a portion of the fleet that burns natural gas. We observed 171 measurements from 73 individual Sterling, Freightliner and Peterbilt trucks with Cummins ISL-G engines that burn natural gas fuel, at stoichiometry, and average 4.4 g/kg of ammonia. These emit very little NO_x (1.0 g/kg) and PM compared to the average of their diesel counterparts. There were also 22 measurements from 17 individual Kenworth trucks with Cummins ISL-X engines that burn natural gas fuel but under very lean A/F conditions similar to diesel engines. These vehicles emit very little ammonia compared to the Sterling trucks (0.02 g/kg or 99.5% less) and they emit much larger levels of NO_x (26.7 g/kg).

Sulfur dioxide emission measurements were very low with no high emitters observed this year compared to measurements observed in 2008, which exposed a number of trucks at the Port of Los Angles that were likely using high sulfur fuels.

Emission intercomparisons between the two remote sensing systems for CO, HC and NO produced generally expected results, with the ESP 4600 underreporting NO emissions relative to the FEAT. The CO and HC comparisons were the most difficult because of the low levels of emissions seen in diesel exhaust. The HC emission levels were consistently low and the correlations were poor with $R^2<0.4$ for both Peralta and the Port. At Peralta the CO comparison had some higher emitters and the correlation showed an R^2 of 0.72. For NO the situation is improved since almost every truck is emitting NO and the range of emissions is large. Both NO correlations have R^2 values greater than 0.78; however the slope of the correlation is approximately 27-30% below the one-to-one line, with the ESP instrument reporting the lower NO values. This is a similar disparity as reported last year despite changing the ESP calibration cylinder.

Introduction

The United States Environmental Protection Agency (EPA) has recently mandated stricter emissions standards for on-road heavy-duty diesel vehicles (HDDVs) with the program represented in Table 1 (*1*). The standards are specifically for reduction of particulate matter (PM), non-methane hydrocarbons (NMHC), and oxides of nitrogen (NO_x). However, beginning in 2007 most diesel engine manufacturers opted to meet a Family Emission Limit (FEL) with EPA allowing engine families with FEL's exceeding the applicable standard to obtain emission credits through averaging, trading and/or banking. This will allow some diesel engine manufacturers to meet 2010+ standards with engines that do not meet a rigid 0.2 g/bhp-hr limit subsequent to the 2010 model year.

Table 1. The 2007 EPA Highway Diesel Program.

Species	Standard (g/bhp-hr)	Phase-In by Model Year			
		2007	2008	2009	2010
NO_x	0.2	50%	50%	50%	100%
NMHC	0.14				
PM	0.01	100%	100%	100%	100%

In California the National EPA Highway Diesel Program is just a part of a number of new regulations that will be implemented over the next decade. The San Pedro Bay Ports Clean Air Action Plan (CAAP) bans all pre-1989 model year trucks starting in October 2008. For all of the remaining trucks it further requires them to meet National 2007 emission standards by 2012. This requirement applies to all trucks, including interstate trucks, which move containers into the South Coast Air Basin and beyond.

The California Air Resources Board (CARB) has implemented a Drayage Truck Regulation that requires by the end of 2009 that all pre-1994 engines be retired or replaced and all 1994 to 2008 engines must meet an 85% PM reduction. By the end of 2013 all drayage trucks must meet 2007 emission standards. This rule applies to all trucks with a gross vehicle weight rating of 33,000 pounds or more that move through port or intermodal rail yard properties for the purposes of loading, unloading or transporting cargo (*2*). In addition, CARB's Statewide Truck and Bus Regulations will phase in most PM requirements for all trucks between 2011 and 2014 and will phase in NO_x emission standards between 2013 and 2023 (*3*).

These regulations will dramatically alter the composition and emission standards of the current South Coast Air Basin's heavy-duty truck fleet, even though the HDDV fleet comprises only 2% of the total on-road population and 4% of the vehicle miles travelled in California's South Coast Air Basin. HDDVs are estimated to account for 40-60% of PM and NO_x emissions in the on-road mobile inventory (*4, 5*).

Before advanced aftertreatment systems, control of NO_x and PM emissions were constrained relative to technologies that trade-off the control of these two pollutants (see

Figure 1). However, advanced control technologies deployed in the post-2007 timeframe for compliance with the U.S. EPA and CARB heavy-duty engine emission standards will not experience this trade-off. These advanced technologies will include a combination of diesel particle filter, selective catalytic reduction, and advanced exhaust gas recirculation (EGR) control strategies. In addition, diesel fuel composition can play a role in emission reductions. The compositions are not studied in this research; however, by measuring sulfur dioxide (SO_2) emissions, we can infer the use of illegal high-sulfur fuels. Overall, understanding the expected impacts of future deployment of advanced emission control technologies will facilitate interpretation of data as it is generated throughout the course of this multi-year research project.

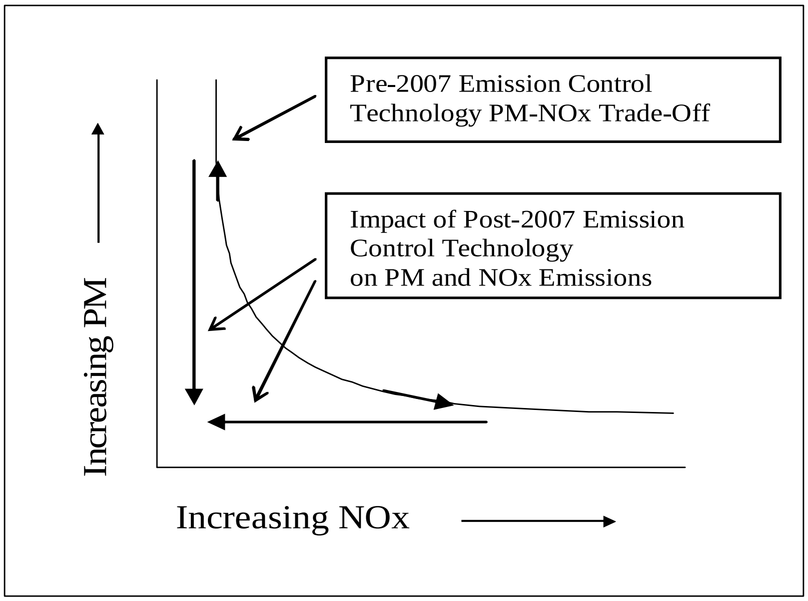

Figure 1. Relative relationship between NO_x and PM emissions in pre-control diesel engines (adapted from Heywood (*7*)). Particle filters, advanced exhaust gas recirculation techniques and selective catalytic reduction systems change this relationship.

This research report specifically contains data from the third year of this multi-year study, to evaluate the impact on heavy-duty diesel emissions as stricter standards are being introduced into the on-road HDDV fleet. HDDV emissions were measured for one week in April 2010 and one week in May 2010 at two locations in California's South Coast Air Basin. CO, HC, NO, NO_2, SO_2, NH_3, and opacity measurements were collected as ratios to their CO_2 reading by the University of Denver equipment. Environmental Systems Products (ESP), the makers of the commercial on-road remote sensor, also had an instrument collecting CO, HC, NO, UV and infrared (IR) smoke data collected also as ratios to CO_2. Speed and acceleration data were also collected.

The study will yield a large database of on-road HDDV emissions for characterization of the fleet. The data collected will allow us to verify the extent to which these new standards are met, to identify trucks not complying with standards, to measure any

increase in NH_3 emissions consequent with the new standards, and also to identify trucks that may be using illegal high-sulfur fuel by measurements of exhaust SO_2.

The research was performed with funding from the South Coast Air Quality Management District (SCAQMD) and the Department of Energy Office of Vehicle Technologies through the National Renewable Energy Laboratory (NREL). Control measures to verify HDDV emissions are typically performed at a special testing facility using a dynamometer. The implementation of remote sensing for this research, however, allows many more trucks to be tested in real-world driving conditions and is significantly less expensive than the dynamometer facility tests.

Experimental

Two remote sensing instruments were set up to measure emissions in a single lane from the elevated plumes of HDDV truck exhausts: RSD 4600 made by ESP and FEAT 3002 equipped with dual UV spectrometers from the University of Denver. The RSD 4600 is a dual beam instrument that consists of a non-dispersive infrared (NDIR) component for detecting CO, CO_2, HC and a dispersive ultraviolet (UV) spectrometer for measuring nitric oxide (NO) and smoke factor at similar wavelengths as those used by the FEAT.

The FEAT 3002 remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust, and has previously been described in the literature (*8 - 10*). The instrument consists of a NDIR component for detecting CO, CO_2, HC, and percent opacity, and two dispersive UV spectrometers for measuring NO, NO_2, SO_2, and NH_3. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Collinear beams of IR and UV light are passed across the roadway into the IR detection unit, and are then focused onto a dichroic beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2, HC, and reference (opacity is determined by plotting reference vs. CO_2). The UV light is reflected off the surface of the beam splitter and is focused onto the end of a quartz fiber-optic cable, which transmits the light to dual UV spectrometers. The UV spectrometers are capable of quantifying NO, NO_2, SO_2, and NH_3 by measuring absorbance bands in the regions of 205 - 226 nm, 429 - 446 nm, 200 - 220 nm, and 200 - 215 nm, respectively, in the UV spectrum and comparing them to calibration spectra in the same regions.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor directly measures only ratios of CO, HC, NO, NO_2, NH_3, SO_2 to CO_2. Appendix A provides a list of the criteria for valid/invalid data. These measured ratios can be converted directly into grams of pollutant per kilogram of fuel. This conversion is achieved by first converting the pollutant ratio readings to the moles of pollutant per mole of carbon in the exhaust from the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 3HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 6(HC/CO_2)} = \frac{(Q, 2Q', Q'')}{Q+1+6Q'}$$

Q represents the CO/CO_2 ratio, Q' represents the HC/CO_2 ratio and Q" represents the NO/CO_2 ratio. Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g., 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in fuel, assuming the fuel is stoichiometrically CH_2. The HC/CO_2 ratio must use two times the reported HC because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon FID reading (*11*). For NG vehicles the appropriate factors for CH_4 are used. Grams per kg fuel can be converted to g/bhp-hr by multiplying by a factor of 0.15 based on an average assumption of 470 g CO_2/bhp-hr (*12*).

The FEAT detectors were calibrated, as external conditions warranted, from certified gas cylinders containing known amounts of the species that were tested. This ensures accurate data by correcting for ambient temperature, instrument drift, etc. with each calibration. Because of the reactivity of NO_2 with NO and SO_2 and NH_3 with CO_2, three separate calibration cylinders are needed: 1) CO, CO_2, propane (HC), NO, SO_2, N_2 balance; 2) NO_2, CO_2, air balance; 3) NH_3, propane, balance N_2.

The FEAT remote sensor is accompanied by a video system that records a freeze-frame image of the license plate of each vehicle measured. The emissions information for the vehicle, as well as a time and date stamp, is also recorded on the video image. The images are stored digitally, so that license plate information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of vehicles driving past the remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generate a pair of infrared beams passing across the road, six feet apart and approximately four feet above the surface. Vehicle speed is calculated from the average of two times collected when the front of the tractors cab blocks the first and the second beam and the rear of the cab unblocks each beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated, and reported in mph/s. An additional set of an emitter and detector are used to cue the FEAT detectors measurement of each truck plume. Appendix B defines the database format used for the data set.

This is the third year of the study to characterize HDDV emissions in the Los Angeles area; the first year's measurements were made in 2008 (*13*); the second year's measurements were made in 2009 (*14*). The 2010 measurements were made on five days at two sites: Peralta weigh station in Anaheim and at the Port of Los Angeles in San Pedro, CA. The Peralta location was chosen in part because it has a history of previous measurements collected in 1997 that can be used for comparison (*15*).

At the Peralta Weigh Station, measurements were made Monday, April 26, to Friday, April 30, between the hours of 8:00 and 17:00 on the lane reentering Highway 91 eastbound (the Riverside Freeway, CA-91 E) after the trucks had been weighed. This weigh station is just west of the Weir Canyon Road exit (Exit 39). A satellite photo showing the weigh station grounds and the approximate location of the scaffolding, motor home and camera is shown in Figure 2. Figure 3 shows a close up picture of the measurement setup. The uphill grade at the measurement location averaged 1.8°. Appendix C lists the hourly temperature and humidity data collected at nearby Fullerton Municipal Airport.

At the Port of Los Angeles, measurements were made on Monday, May 3, to Friday, May 7, between the hours of 8:00 and 17:00 just beyond the exit kiosk where truckers had checked out of the port. This location is just west of the intersection of West Water Street and South Fries Avenue. A satellite photo of the measurement location is shown in Figure 4 and a close up picture of the setup is shown in Figure 5. The grade at this measurement location is 0°. Appendix C lists the hourly temperature and humidity data collected at nearby Daugherty Field in Long Beach.

The detectors were positioned on clamped wooden boards atop aluminum scaffolding at an elevation of 13’3”, making the photon beam and detector at an elevation of 14’3” (see Figures 3 and 5). The scaffolding was stabilized with three wires arranged in a Y shape. A second set of scaffolding was set up directly across the road on top of which the transfer mirror module (ESP) and IR/UV light source (FEAT) were positioned. The light source for the RSD 4600 is housed with the detector in the instrument and is shone across the road and reflected back. Behind the detector scaffolding was the University of Denver’s mobile lab housing the auxiliary instrumentation (computers, calibration gas cylinders and generator). Speed bar detectors were attached to each scaffolding unit which reported truck speed and acceleration. A video camera was placed down the road from the scaffolding, taking pictures of license plates when triggered.

At the Peralta weigh station, detection took place on the single lane at the end of the station where trucks were reentering the highway. Most trucks were traveling between 10 and 20 mph in an acceleration mode to regain speed for the upcoming highway merger.

The Port of Los Angeles testing site was located at an exit near the intersection of Fries Avenue and Water Street near Wilmington, CA. The exit has three lanes allowing trucks to leave (one reserved for bobtails), and our equipment was set up in Lane #1 about 30 feet down the road from a booth where trucks stopped to check out of the Port. At the Port location the trucks were accelerating from a dead stop generally not reaching speeds higher than 5 mph.

Figure 2. A satellite photo of the Peralta weigh station located on the eastbound Riverside Freeway (State Route 91). The scales are located on the inside lane next to the building in the top center and the outside lane is for unloaded trucks. The measurement location is circled at the upper right with approximate locations of the scaffolding, support vehicle and camera.

Figure 3. Photograph at the Peralta Weigh Station of the setup used to detect exhaust emissions from heavy-duty diesel trucks.

Figure 4. A satellite photo of the Port of Los Angeles Water Street. exit. The measurement location is circled in the lower left with approximate locations of the scaffolding, support vehicle and camera.

Figure 5. Photograph at the Port of Los Angeles of the setup used to detect exhaust emissions from heavy-duty diesel trucks.

Results and Discussion

The five days of data collection using the University of Denver FEAT remote sensor at the Peralta weigh station resulted in 2120 license plates that were readable. Plates were not read for the ESP equipment. While California plated trucks constituted the large majority of the trucks measured, there were 350 measurements from trucks registered outside of California. Table 2 details the registration, the total measurements and the number of unique trucks they represent. License plates were matched for California, Arizona, Washington, Texas, Oklahoma and Illinois trucks.

Data collected during the five days of measurements using the University of Denver FEAT remote sensor at the Port of LA site resulted in 2109 license plates that were readable. The plates were not read for the ESP equipment at this site. There were only 146 out–of-state plated trucks measured at the Port. Table 3 details the registration, the total measurements and the number of unique trucks measured. License plates were matched for the California, Illinois, Texas and Arizona vehicles.

Table 4 provides a data summary of the previous and current measurements that have been collected at the two measurement sites. From 1997 to 2010 reductions in CO (34%) and HC (15%) and NO (23%) emissions have been observed at Peralta. License plates were not read and matched during the 1997 measurements, so we are unable to comment with any certainty on how fleet changes during the past twelve years may have contributed to these reductions.

Table 5 provides a data summary comparison of the California-plate-matched trucks against the matched out-of-state trucks measured at the Peralta weigh station and compares their age and emission measurements. To simplify this comparison we required a valid measurement for each species so that the numbers of vehicles are consistent across all of the columns. The small sample of out-of-state trucks is almost 3.2 chassis model years newer with all emissions being lower.

Fleet composition and driving mode are again noticeably different between the two sites sampled in 2010. The Port of Los Angeles fleet is almost six years newer than the Peralta fleet and the measurements observe a high load, low speed acceleration as the trucks move away from the checkout gate. Figure 6 shows the fleet fractions (calculated by dividing the number of HDDV in each model year by the total number of HDDV vehicles in the database for that location) as a function of model year for Peralta and the Port. There has been a large and fast change in the average fleet age at the Port as part of the CAAP getting about twelve years newer in the last two years. The average fleet age at Peralta has regressed getting about half a year older, not newer, in the last two years. The age distribution at Peralta shows that the fraction of model years 2008 and newer is very low compared to the Port. A higher purchase rate of 2007 HDDVs prior to the introduction of new technology engines combined with the national economic downturn in 2008 have reduced the emissions that might have occurred at the Peralta sight.

Table 2. Distribution of Identifiable Peralta License Plates.

State / Country	Readable Plates	Unique Plates	Matched Unique Plates	Total Measurements
Alabama	3	3	0	0
Arizona	38	36	30	32
California	1770	1432	1420	1761
Colorado	1	1	0	0
Florida	4	4	0	0
Georgia	2	2	0	0
Iowa	5	5	0	0
Idaho	3	3	0	0
Illinois	45	41	41	45
Indiana	82	78	0	0
Kansas	2	2	0	0
Louisiana	1	1	0	0
Massachusetts	1	1	0	0
Michigan	2	2	0	0
Minnesota	6	6	0	0
Montana	3	2	0	0
North Carolina	11	11	0	0
North Dakota	2	2	0	0
Nebraska	4	4	0	0
New Jersey	5	5	0	0
New Mexico	2	2	0	0
Nevada	7	7	0	0
New York	1	1	0	0
Ohio	10	10	0	0
Oklahoma	21	17	16	20
Oregon	23	20	0	0
Pennsylvania	3	3	0	0
Tennessee	14	11	0	0
Texas	15	15	6	6
Utah	14	14	0	0
Washington	8	8	7	7
Wisconsin	4	4	0	0
Canada	8	8	0	0
Totals	2120	1761	1520	1871

Table 3. Distribution of Identifiable Port of Los Angeles License Plates.

State	Readable Plates	Unique Plates	Unique Matched Plates	Total Measurements
Arizona	29	17	7	8
California	1963	1103	1095	1956
Illinois	3	3	3	3
Indiana	54	40	0	0
New Jersey	1	1	0	0
Ohio	29	19	0	0
Oklahoma	7	2	1	2
Oregon	6	5	0	0
Texas	16	11	10	15
Utah	1	1	0	0
Totals	2109	1202	1116	1984

Table 4. Peralta Weigh Station and Port of Los Angeles FEAT Data Summary.

Location Study Year	Peralta 1997	Peralta 2008	Peralta 2009	Peralta 2010	Port of LA 2008	Port of LA 2009	Port of LA 2010
Mean CO/CO_2 (g/kg of fuel)	0.008 (16.1)	0.005 (10.0)	0.005 (10.6)	0.005 (10.0)	0.006 (12.7)	0.004 (7.6)	0.005 (8.6)
Median gCO/kg	9.3	6.7	6.6	6.6	10.6	4.0	2.7
Mean HC/CO_2 (g/kg of fuel)	0.0008 (5.0)	0.0004 (2.7)	0.0007 (4.8)	0.0007 (4.2)	0.0009 (5.3)	0.0009 (5.4)	0.0009 (5.2)
Median gHC/kg	3.7	2.1	2.9	2.9	4.2	3.3	2.5
Mean NO/CO_2 (g/kg of fuel)	0.009 (19.2)	0.008 (16.4)	0.007 (15.4)	0.006 (14.7)	0.013 (27.1)	0.008 (17.7)	0.006 (13.6)
Median gNO/kg	18.0	15.2	14.3	13.5	24.8	14.9	12.4
Mean SO_2/CO_2 (g/kg of fuel)	NA	0.00006 (0.26)	0.00004 (0.16)	-0.00004 (-0.22)	0.00004 (0.18)	-0.000004 (-0.016)	-0.00005 (-0.23)
Median gSO_2/kg	NA	0.22	0.11	-0.2	0.16	-0.003	-0.2
Mean NH_3/CO_2 (g/kg of fuel)	NA	0.00003 (0.03)	0.00002 (0.003)	0.000007 (0.008)	0.00001 (0.02)	0.0002 (0.2)	0.0004 (0.4)
Median gNH_3/kg	NA	0.02	0.016	0.006	0.02	0.01	0.02
Mean NO_2/CO_2 (g/kg of fuel)	NA	0.0006 (2.1)	0.0006 (1.9)	0.0005 (1.9)	0.001 (3.9)	0.001 (3.3)	0.0008 (2.5)
Median gNO_2/kg	NA	1.6	1.4	1.4	3.4	2.4	1.2
Mean gNO_x/kg	NA	27.3	25.4	25.4	45.4	30.4	23.3
Median gNO_x/kg	NA	25.2	23.6	22.3	41.7	26.1	21.9
Mean Model Year	NA	2000.4	2001.3	2002.0	1995.6	2003.5	2007.9
Mean Speed (mph)	NA	13.4	13.5	13.4	~<5	4.6	5.0
Mean Acceleration (mph/s)	NA	1.1	0.9	0.8	NA	0.5	0.5
Mean VSP(kw/tonne) Slope (degrees)	NA 1.8°	6.3 1.8°	5.8 1.8°	4.9 1.8°	NA 0°	1.0 0°	1.0 0°

Table 5. Peralta emission summary comparison for California and out-of-state plate matched trucks.

State	Trucks	Mean gCO/kg	Mean gHC/kg	Mean gNO/kg	Mean gNO_2/kg	Mean gNO_x/kg	Mean gSO_2/kg	Mean gNH_3/kg	Mean Model Year
CA	1761	10.2	4.3	14.9	2.0	24.8	-0.22	0.009	2001.8
Other	110	6.1	2.8	11.8	1.3	19.4	-0.16	0.004	2005
Δ		40%	35%	21%	35%	22%	27%	55%	-3.2

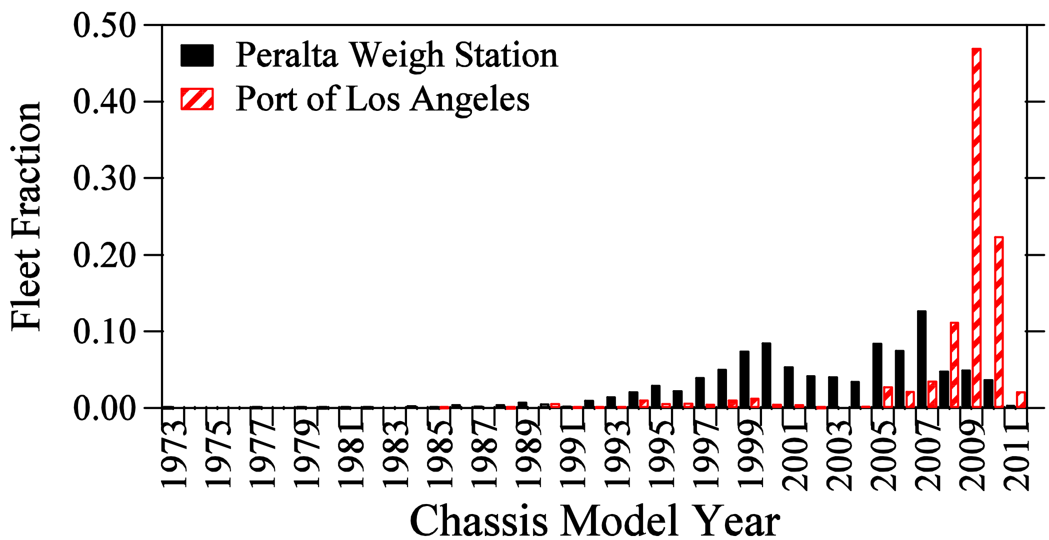

Figure 6. Fleet fractions versus model year for the Peralta weigh station and the Port of Los Angeles.

Figures 7 and 8 plot mean NO_x emissions at both locations as a function of chassis model year for the measurement years 2008 through 2010. These are the only consecutive on-road HDDV measurements in the field taken from the same sites. Measurements at Peralta show good agreement for both years with decreasing mean NO_x emissions as a function of chassis model year. Measurements at the Port decrease as well but there are no comparative measurements for model years 2008-2010 taken in 2008. Figure 9 plots the cumulative fraction of NO_x emissions against the fraction of the fleet. In 2008 the distributions were nearly identical. For measurements made in 2009, there was a measurable separation of emission distributions with 10% of the Peralta fleet producing 20% of NO_x emissions and 10% of the Port fleet producing 24% of emissions. This difference was thought to be a result of the interjection of new trucks at the Port starting in 2009, but in 2010 the distributions are nearly identical which is similar to measurements in 2008.

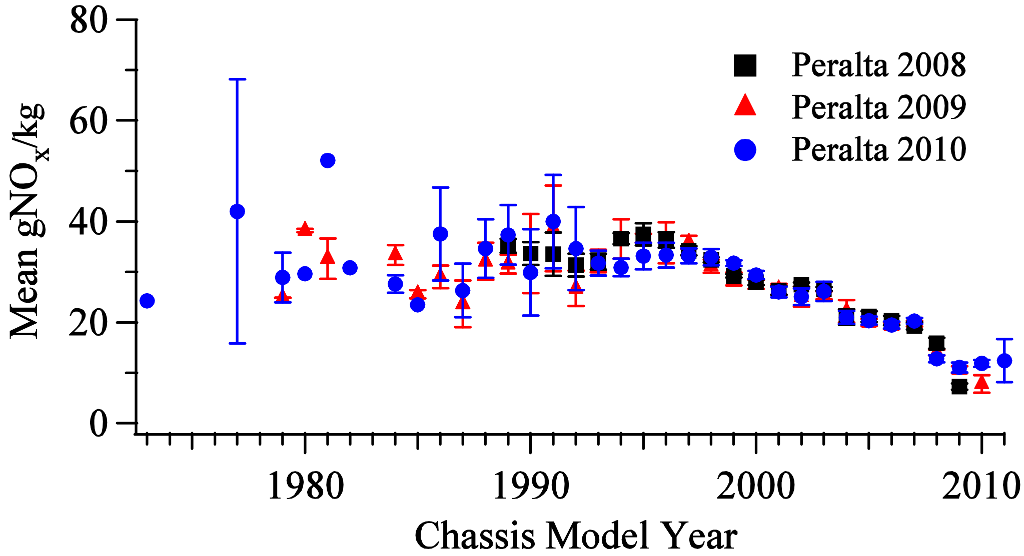

Figure 7. Mean NO_x emissions for 2008-2010 measurements at Peralta Weigh Station. Both years show a general trend of decreasing mean NO_x as a function of chassis model year.

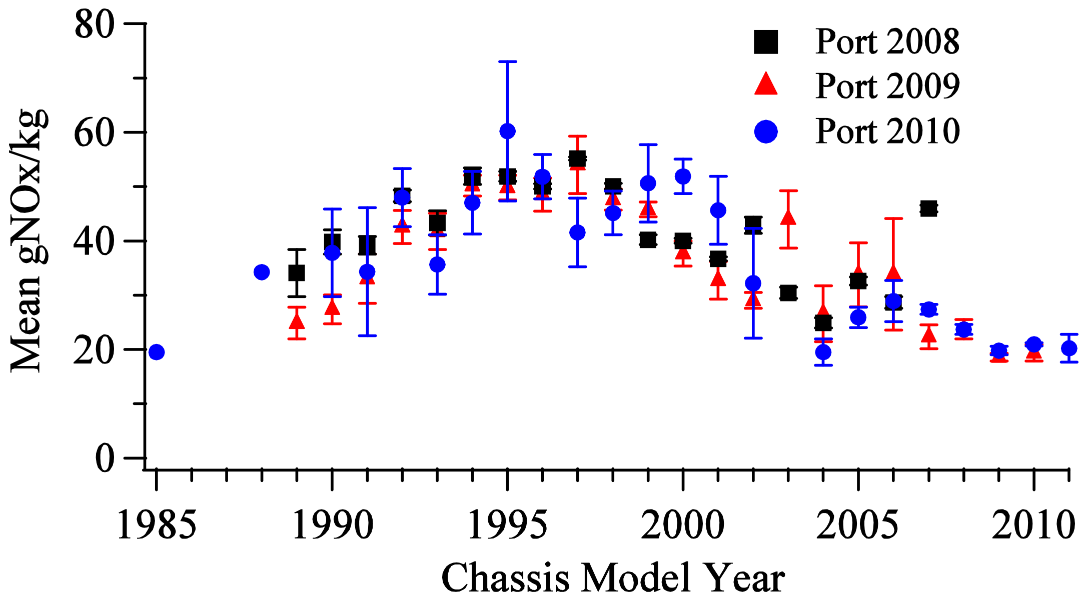

Figure 8. Mean NO_x emissions for 2008-2010 measurements at the Port of LA. Both years show a general trend of decreasing mean NO_x as a function of chassis model year.

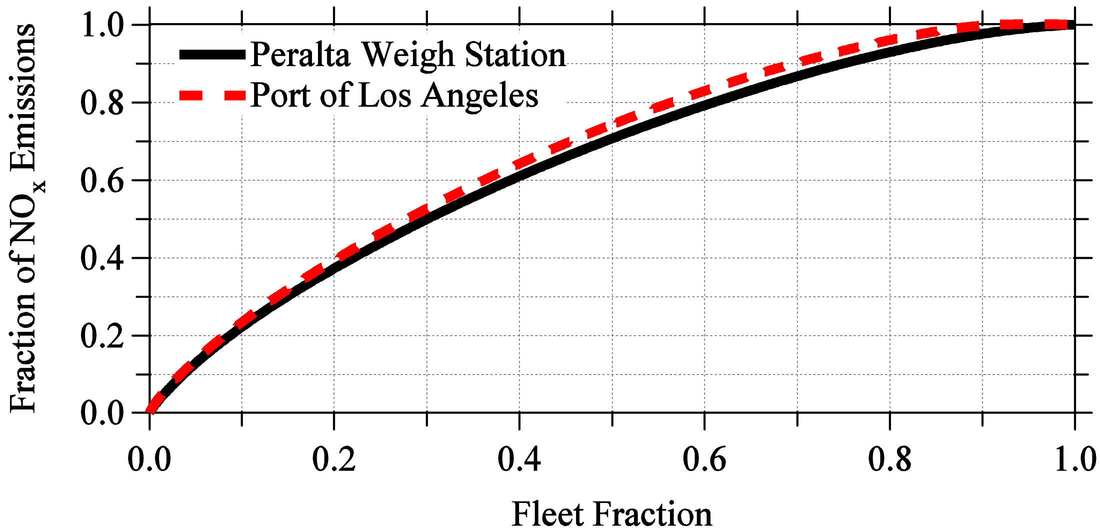

Figure 9. Cumulative NO_x emissions plotted versus the fraction of the truck fleet for the 2010 Peralta weigh station and Port of Los Angeles measurements.

The National and California emission regulations that have targeted major reductions in PM emissions have been met with the introduction of diesel particle filters (DPF). Because these filters physically trap the particles, they require a mechanism to oxidize the trapped particles to keep the filter from plugging. One approach used to date has been to install an oxidation catalyst upstream of the filter and to use it to convert engine-out NO emissions to NO_2. NO_2 is then capable of oxidizing the trapped particles to regenerate the filter and is able to accomplish this at lower temperatures than is possible with other species. However, if the production of NO_2 is not controlled well it can lead to an increase in tailpipe emissions of NO_2, and the unintended consequence of increased ozone in urban areas (*16, 17*).

European experiences with increasing the prevalence of DPF's have shown a correlation with increases in urban NO_2 emissions (*18*). California has codified this concern by passing rules that limit any increases in NO_2 emissions from the uncontrolled engine baseline emissions for retrofit DPF devices (*19*). Nationally, new vehicle manufacturers are constrained with only a total NO_x standard that does not differentiate between NO and NO_2 emissions. Traditionally diesel exhaust NO_2 has comprised less than 10% of the tailpipe NO_x emissions; however this ratio has increased in the new trucks. Figure 10 presents on-road data for NO_2/NO_x ratio of HDDV emissions by model year. Nearly the entire fleet of the newest trucks (model year 2008-2011) have been fitted with one of these PM-reducing devices in accordance with the new EPA standards. The result is an observed increase in the NO_2/NO_x ratio in line with the expectation of increased emissions of NO_2.

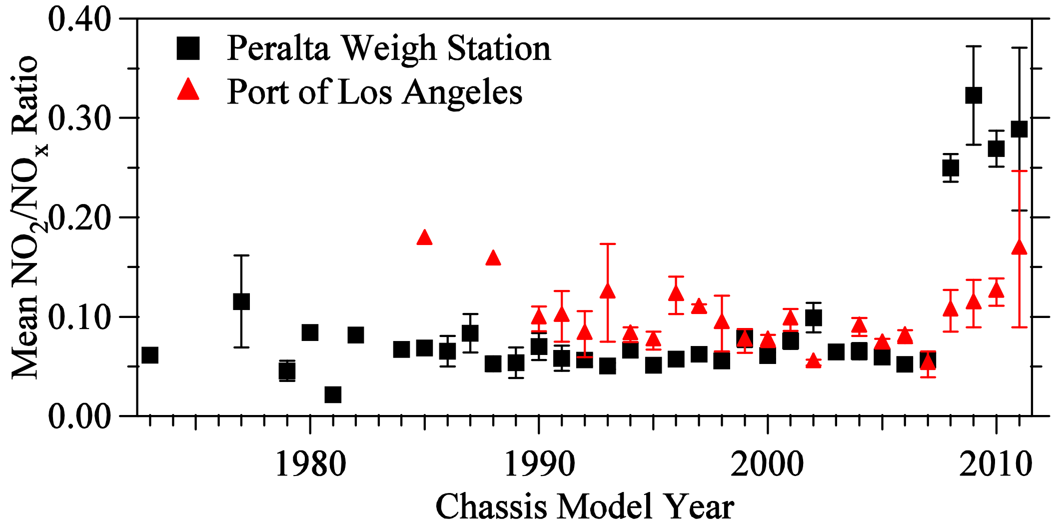

Figure 10. Ratio of NO_2/NO_x vs. chassis model year for HDDV's at each site. New technologies implemented to meet new EPA standards yield higher proportions of NO_2 in MY 2008-2011 trucks. Uncertainties are standard errors of the mean.

As the diesel particle filters are being phased into the fleet we would expect to observe large reductions in PM emissions. Figure 11 shows the PM emissions recorded by the two remote sensing systems and combines both sites' emissions and averages them against their chassis model year. Combining both sites PM emissions was decided after observing that the slope intercomparisons of the three measurement channels were identical for both sites. The FEAT system measures percent opacity in the infrared while the RSD 4600 reports a smoke factor value in both the infrared and the ultraviolet. A UV smoke factor of 0.1 is equivalent to 1 gram of soot per kilogram of fuel. We report their results in these units. As shown in Figure 11, decreased particle emissions are observed with both systems beginning with the 2008 model chassis. The PM standard of 0.01 g/bhp-hr translates to a cycle average of 0.07 g/kg. The 2009 measurements showed that the newer model years were certainly approaching this value. The 2010 measurements continue to show low smoke values for the newer model years 2007-2011. Figure 12 shows the cumulative smoke emission distributions for the three metrics and indicates that the overall emissions distribution for smoke at the combined sites is not heavily skewed towards high emitters. The apparent emission fraction above 1.0 results from negative smoke readings that arise from instrument noise.

Another goal of the research was to quantify ammonia emissions over the five-year period. Ammonia is a potential byproduct of methods to be implemented to reduce NO_x emissions in diesel trucks to meet the 2010 EPA standards. In a recent study on light-duty vehicles, Bishop *et al.* (*20*) found that the mean ammonia emitted by California cars is 0.49 g/kg. These emissions come about as a by-product of NO reduction in the presence of hydrogen by three-way catalysts in the light-duty vehicles.

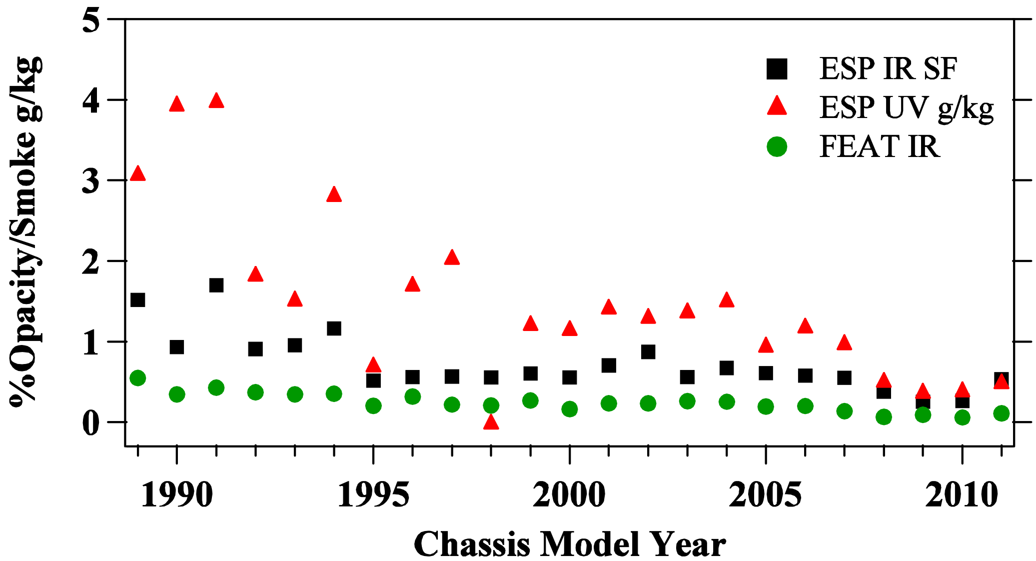

Figure 11. Combined smoke measurements of Peralta and the Port of Los Angeles as a function of model year for the two remote sensing systems. The FEAT reports a % Opacity from the infrared and the ESP system reports smoke (g/kg) in the infrared and the ultraviolet. Model years dating before 1989 are removed because of low sample sizes and high noise.

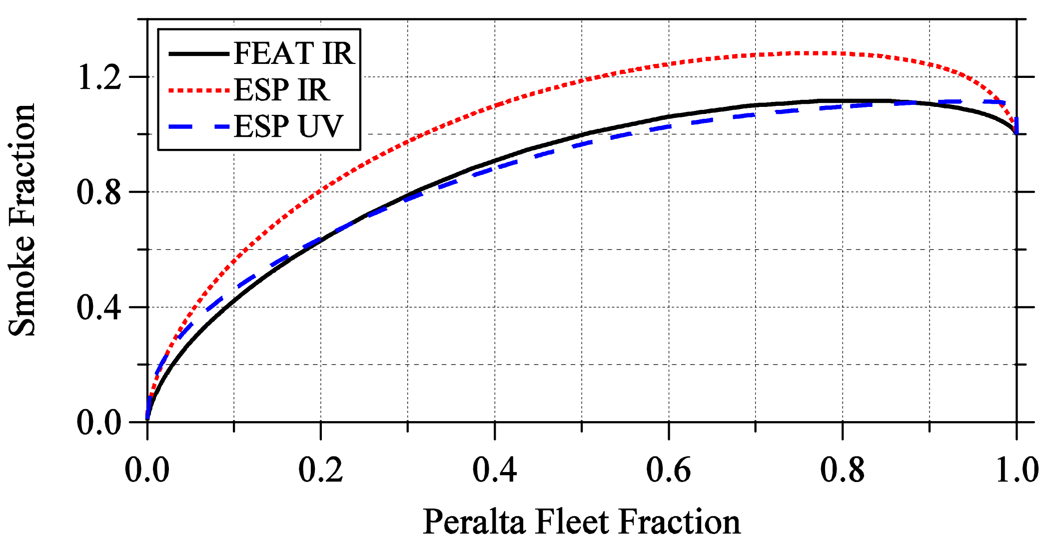

Figure 12. Matched emission data sets of combining Peralta and the Port of Los Angeles for the FEAT and ESP 4600 plotting the cumulative total emission for the infrared and ultraviolet smoke measurements. The fact that 10% of the fleet accounts for approximately 40% of the smoke emissions indicates that the distributions are only slightly skewed.

The 2010 measurements observed the same two types of vehicles, that were documented in 2009, at the Port which burn natural gas fuel. The first was a group of Cummins ISL-G engines that have been implemented in Sterling, Peterbilt and Freightliner trucks that burn LNG at stoichiometry with a three-way catalyst with reducing conditions. The second was a group of Kenworth vehicles with Cummins ISX engines burning LNG but under very lean air/fuel (A/F) ratio conditions similar to diesel engines with an oxidation catalyst (See Appendix E). The Cummins ISL-G engine is a gasoline equivalent spark ignition engine combined with Exhaust Gas Recirculation (EGR). The EGR system takes a measured amount of exhaust gas and passes it through a cooler to reduce temperature before mixing it with fuel and incoming air. This helps reduce combustion temperature and improves power density; however, ultimately methane does not completely burn and the catalyst is overwhelmed by excess hydrogen. Ammonia is a byproduct of the reducing conditions of the three-way catalyst and thus excess hydrogen reduces NO to ammonia. The Cummins ISX engine is a dual fuel (diesel and LNG) compression ignition system that operates under very lean conditions. The oxidation catalyst serves to oxidize non-methane hydrocarbons, carbon monoxide and particles, but does not have the required reducing conditions to reduce NO to ammonia. By itself, methane combusts very poorly under compression ignition, and to help ignite the methane the Cummins ISX adds a small amount of diesel fuel to the cycle. This produces many tiny diesel droplets combusting in the cylinder and acting as flame ignition points for the lean methane air mixture. By comparison, the Cummins ISL-G has only one flame ignition point which is the spark plug.

Figure 13 is a bar chart separating trucks at the Port into the types of fuel they burn and the corresponding mean emission for NO_x, ammonia and opacity. The lean burning natural gas NO_x and opacity emissions are similar to the diesel emissions. The average opacity of the lean burn natural gas trucks is similar to the average opacity of diesel trucks of equivalent model year; however the average diesel opacity is distinguishable from zero while the lean burn natural gas trucks are indistinguishable from zero. On the other hand the stoichiometric burning natural gas emissions are very dissimilar than the other fuel types. They emit very little NO_x and PM but emit a very large amount of ammonia (~5g/kg). In 2010, the average PM for the stoichiometric natural gas engines is higher than the average for equivalent model years of diesel trucks. The 2007-2011 model years of diesel trucks are required to meet the PM standard of 0.01 g/bhp-hr and most trucks do so with a DPF. However, while diesel trucks use DPFs to reduce PM emissions natural gas engines do not utilize DPFs because they are thought to start with lower PM emissions. These trucks with ISL-G engines have ground-level exhaust plumes and did not get captured by the instruments on every pass, because the optical beams are greater than thirteen feet above the ground.

An analysis of the 2010 SO_2 emissions from both locations, shows that the average for HDDVs in 2010 is -0.22 g/kg and that there are no high SO_2 emitters which were present in the Bishop *et al.* 2008 report (*13*). The use of 15 ppm ultra-low sulfur diesel fuel is required by law in North America starting from September 2006 (*21*). Figure 14 is a plot of all of the valid measurements from both locations. In this format it was easy to spot the outliers from the 2008 measurements where trucks who cheated with

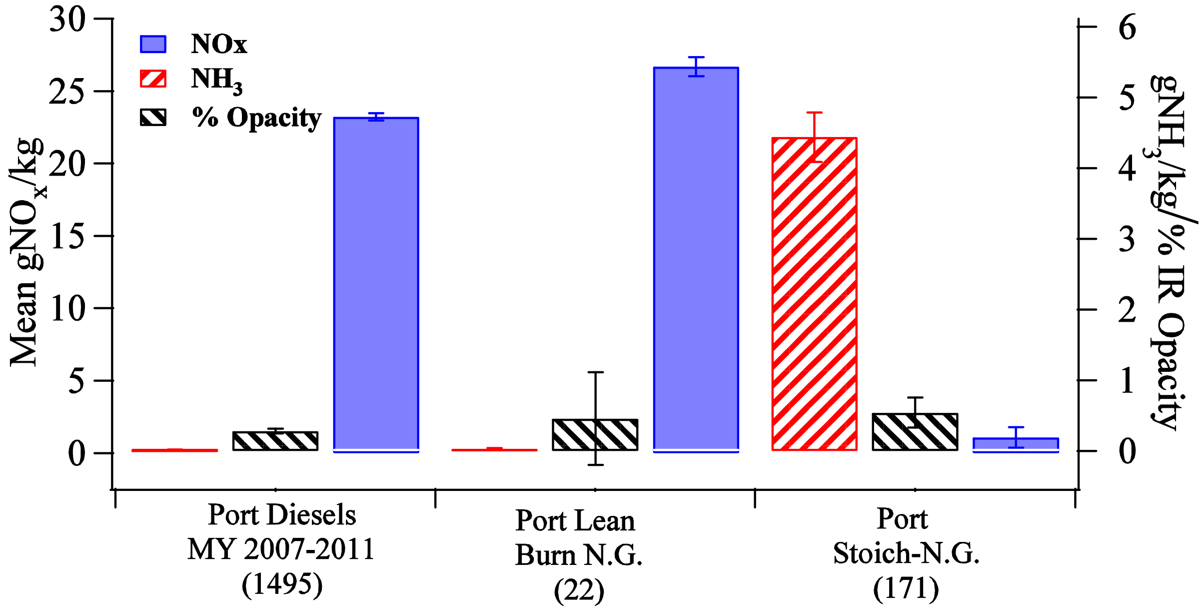

Figure 13. Bar chart of mean emissions of NO_x, ammonia and opacity by type of fuel burned and engine type from HDDVs at the Port. Numbers in parentheses are sample sizes. Opacity sample sizes are 1448, 20 and 104 for Diesel, Lean NG and Stoich-NG respectively. Error bars are standard error of the mean.

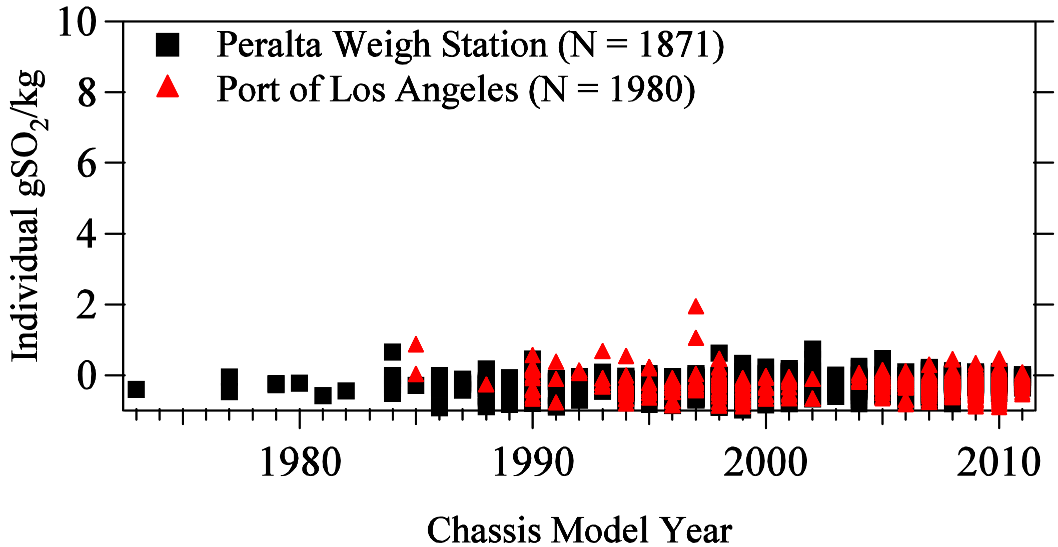

Figure 14. Individual SO_2 emission readings by model year. The SO_2 outliers present in the 2008 data are absent in this year's study.

>15ppm or high-sulfur fuel could be identified. However, the 2010 measurements show no outliers compared to measurements taken in 2008.

Using the trucks with readable plates we matched emission measurements on trucks captured by both remote sensing devices. Each day's database was compared, using the recorded photographs, to determine the time differences between the two data sets. After determining this difference it was possible to time align the two sets of measurements to within ± 1 second for the entire day's data. The readings were then manually matched with each other and any questionable matches were resolved using the video images.

Figures 15 and 16 compare the two time-aligned databases for CO, HC and NO with the line plotted being a least squares fit through the data points. The equation included provides the slope and intercept for the least squares line. At Peralta there are 1289 matched measurements and at the LA Port there are 1182 matched measurements. The data collected at the Port have noticeably more noise than the measurements collected at Peralta, and this is likely a consequence of the low-speed driving mode observed at the Port. In addition there are a number of negative readings reported by the FEAT while the ESP equipment has few if any negative readings. This is a result of the two different ways that the remote sensors calculate the emission ratios. The FEAT determines the emission ratios from a least squares line fit through the correlated emissions plume data. Fits close to zero will always have positive and negative results. The ESP equipment on the other hand uses an integral method where each species plume data are summed and then the ratios are calculated from these sums. This method produces fewer negative results.

Generally only the NO measurements have enough spread to lend themselves to being compared. While the noise is greater for the NO data collected at the Port both data sets have a similar slope with the ESP instrument consistently reporting lower NO emissions when compared with the FEAT measurements. Keep in mind that the two remote sensing beams were separated by about three feet and we did not try to collocate them and as such some disagreement, because of differences in driving mode, will be unavoidable. However, the systematic underreporting of NO by the ESP equipment appears to be much larger than one would expect a driving mode difference to produce.

While there are major operational differences between FEAT and the RSD 4600 they both basically operate as comparators that compare the ratios of a standard gas cylinder with the ratios measured from the passing trucks. Since the systematic difference between the two instruments was observed in the field at Peralta it was decided to compare the two calibration cylinders at the LA Port. It was a simple matter to use ESP's cylinder on the FEAT instrument and using the Port setup we first used the FEAT to measure its calibration cylinder and then we repeated measurements on the ESP cylinder. Both cylinders were products of Scott Specialty Gases and Table 6 details those measurements.

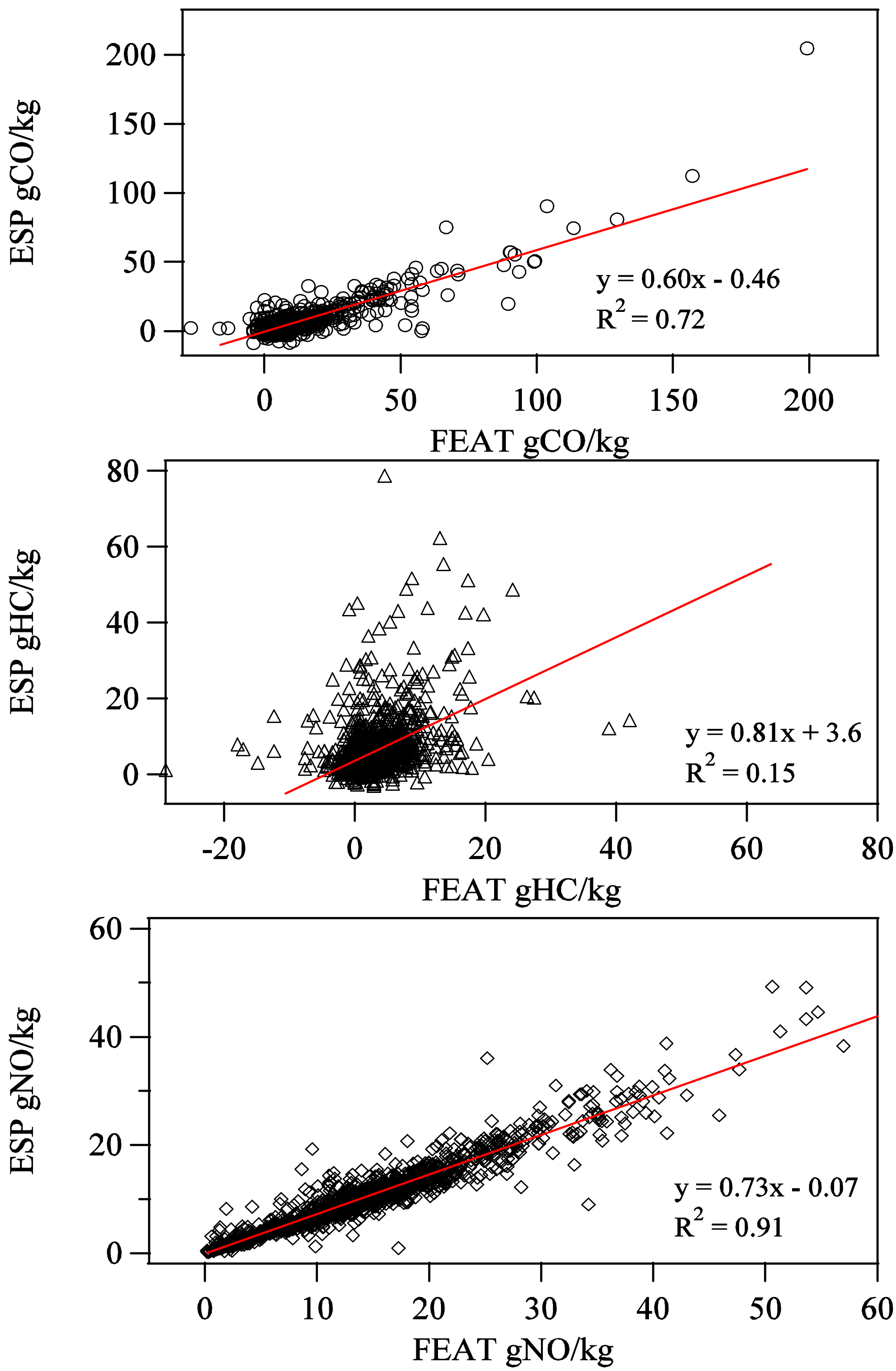

Figure 15. A total of 1289 time aligned emission measurements for CO, HC and NO collected at the Peralta weigh station by the two remote sensing systems. A least squares best fit line is plotted for each ratio and the equation for that line is included.

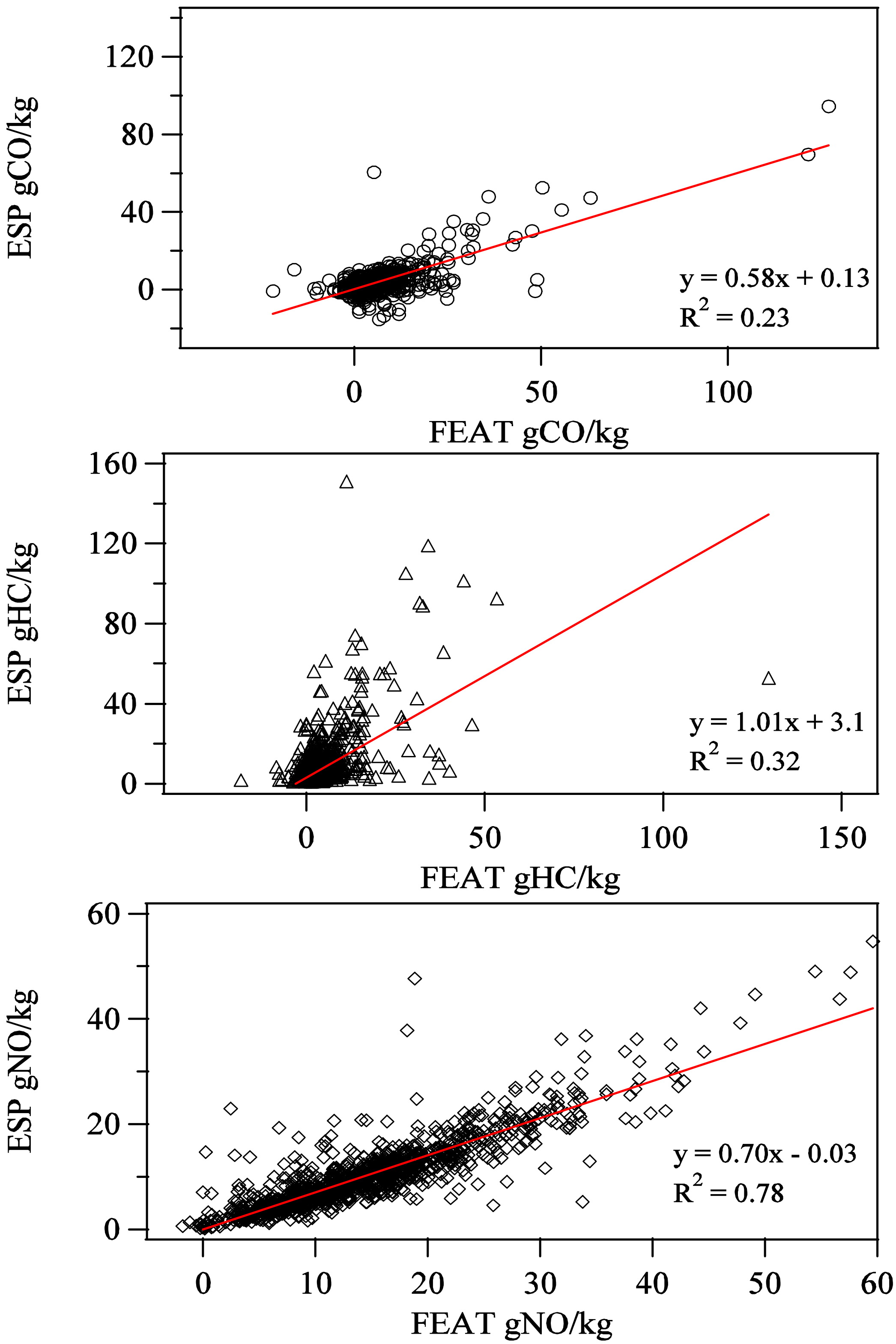

Figure 16. A total of 1182 time aligned emission measurements for CO, HC and NO collected at the LA Port by the two remote sensing systems. A least squares best fit line is plotted for each ratio and the equation for that line is included.

Table 6. Results of using the FEAT remote sensor to compare calibration cylinders

	FEAT Cylinder			ESP Cylinder		
	CO/CO_2	HC/CO_2	NO/CO_2	CO/CO_2	HC/CO_2	NO/CO_2
	0.985	0.1019	0.046	0.296	0.01176	0.01573
	0.978	0.1014	0.047	0.287	0.01203	0.01563
	1.017	0.1062	0.046	0.287	0.01195	0.01499
Mean	0.993	0.1032	0.046	0.290	0.01191	0.01545
Cylinder Ratio	1	0.0996	0.0499	0.2326	0.0116	0.0116
Cal Factor	0.99	1.04	0.92	1.25	1.03	1.33
Percent Difference				+26%	Negligible	+45%

The procedure was to simply puff each cylinder into the FEAT's light path and record the ratio that it measured. We then averaged each set of readings and ratioed that to the reported ratios in the calibration cylinders producing a calibration factor that would normally be used to compare that cylinder to the exhaust measurements being made from the trucks. Ideally each cylinder would produce approximately the same calibration factors. The fact that the ESP cylinder calibrations are all larger relative the FEAT cylinder indicates that the two certified cylinders do not agree on their contents and that the FEAT would underreport each ratio if the ESP cylinder was used for calibration. From this comparison it is impossible to say which cylinder is off but the disagreement between the two cylinders NO/CO_2 ratios possibly explains the observed differences in slopes between the comparisons of truck emissions with the two remote sensors. The lower slopes at Peralta were 60 and 73% for CO and NO respectively. We chose not to consider HC emissions here because they are consistently low and the correlations are poor at both locations. If we simply add the percent discrepancy for the ESP cylinder versus the FEAT cylinder, we obtain the results 86% (CO) and 118% (NO) which implies that both instruments were actually measuring the same phenomenon within the constraints imposed by the calibration cylinder disagreement.

Acknowledgements

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References

1. USEPA Highway Diesel Progress Review, 2002, http://www.epa.gov/oms/highway-diesel/compliance/420r02016.pdf.
2. California Code of Regulations, Title 13, Section 2027, 2008.
3. California Code of Regulations, Title 13, Section 2025, 2008.
4. 2006 Estimated Annual Average Emissions: Statewide. http://www.arb.ca.gov/ei/emissiondata.htm, California Air Resources Board, 2007.
5. Harley, R.A.; Marr, L.C.; Lehner, J.K.; Giddings, S.N. *Environ. Sci. Technol.*, **2005**, *39*, 5356-5362.
6. McCormick, R. L.; Ross, J. D.; Graboski, M. S. *Environ. Sci. Tech.*, **1997**, *31*, 1144-1150.
7. Heywood, J. B. Internal Combustion Engine Fundamentals, McGraw-Hill Publishing: New York, p. 866, 1988.
8. Bishop, G.A.; Stedman, D.H. *Acc. Chem. Res.* **1996**, *29*, 489.
9. Popp, P.J.; Bishop, G.A.; Stedman, D.H. *J. Air & Waste Manage. Assoc*. **1999**, *49*, 1463.
10. Burgard, D.A.; Dalton, T.R.; Bishop, G.A.; Starkey, J.R.; Stedman, D.H. *Rev. Sci. Instrum.* **2006**, *77*, 014101.
11. Singer, B.C.; Harley, R.A.; Littlejohn, D.; Ho, J.; Vo, T. *Environ. Sci. Technol.* **1998**, *32*, 3241.
12. Broering, L. C. *Diesel Engine Emissions Reduction History and Future Prospects*, Cummins Engine Company, Presentation at the National Conference of State Legislatures, 1997.
13. Bishop, G.A.; Holubowitch, N.E.; Stedman, D.H. Remote Measurements of On-Road Emissions from Heavy-Duty Diesel Vehicles in California; Year 1, 2008.
14. Bishop, G.A.; Schuchmann, B.S.; Stedman, D.H. Remote Measurements of On-Road Emissions from Heavy-Duty Diesel Vehicles in California; Year 2, 2009.
15. Bishop, G.A.; Morris, J.A.; Stedman, D.H.; Cohen, L.H.; Countess, R.J; Countess, S.J.; Maly, P.; Scherer, S. *Environ Sci. & Technol.*, **2001**, *35*, 1574-78.
16. Stedman, D.H. *Environ. Chem.*, **2004**, *1*, 65-66.
17. Lawson, D.R., The Weekend Ozone Effect—The Weekly Ambient Emissions Control Experiment *EM*, July 2003, pp. 17-25.
18. Lemaire, J. *Österreichische Ingenieur und Architekten-Zeitschrift*, **2007**, *152*, 1-12, http://www.feat.biochem.du.edu/library/Lemaire_2007.pdf.
19. California Code of Regulations, Title 13, Section 2702(f) and 2706(a), 2003.
20. Bishop, G.A.; Peddle, A.M.; Stedman, D.H.; Zhan, T. *Environ. Sci. Technol.* **2010**, *44*, 3616.
21. USEPA 2007 Highway Rule, http://www.epa.gov/otaq/highway-diesel/index.htm.

http://www.us.sgs.com/ulsd_testing.htm?serviceId=10010630&lobId=19649

APPENDIX A: FEAT criteria to render a reading "invalid".

Invalid :

1) insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms >160ppm CO_2 or >400 ppm CO. (0.2 %CO_2 or 0.5% CO in an 8 cm cell. This is equivalent to the units used for CO_2 max.). For HDDV's this often occurs when the vehicle shifts gears at the sampling beam.

2) excessive error on CO/CO_2 slope, equivalent to $\pm$20% for CO/CO_2 > 0.069, 0.0134 CO/CO_2 for CO/CO_2 < 0.069.

3) reported CO/CO_2 , < -0.063 or > 5. All gases invalid in these cases.

4) excessive error on HC/CO_2 slope, equivalent to $\pm$20% for HC/CO_2 > 0.0166 propane, 0.0033 propane for HC/CO_2 < 0.0166.

5) reported HC/CO_2 < -0.0066 propane or > 0.266. HC/CO_2 is invalid.

6) excessive error on NO/CO_2 slope, equivalent to $\pm$20% for NO/CO_2 > 0.001, 0.002 for NO/CO_2 < 0.001.

7) reported NO/CO_2 < -0.00465 or > 0.0465. NO/CO_2 is invalid.

8) excessive error on SO_2/CO_2 slope, ± 0.0134 SO_2/CO_2.

9) reported SO_2/CO_2 , < -0.00053 or > 0.0465. SO_2/CO_2 is invalid.

10) excessive error on NH_3/CO_2 slope, ± 0.00033 NH_3/CO_2.

11) reported NH_3/CO_2 < -0.00053 or > 0.0465. NH_3/CO_2 is invalid.

12) excessive error on NO_2/CO_2 slope, equivalent to $\pm$20% for NO_2/CO_2 > 0.00133, 0.000265 for NO_2/CO_2 < 0.00133.

13) reported NO_2/CO_2 < -0.0033 or > 0.0465. NO_2/CO_2 is invalid.

Speed/Acceleration valid only if at least two blocks and two unblocks in the time buffer and all blocks occur before all unblocks on each sensor and the number of blocks and unblocks is equal on each sensor and 100mph>speed>5mph and 14mph/s>accel>-13mph/s and there are no restarts, or there is one restart and exactly two blocks and unblocks in the time buffer.

APPENDIX B: Explanation of the Peralt10.dbf and LAPort10.dbf databases.

The Peralt10.dbf and LAPort10.dbf are Microsoft FoxPro database files, and can be opened by any version of MS FoxPro. These files can be read by a number of other database management and spreadsheet programs as well, and is available from www.feat.biochem.du.edu. The grams of pollutant/kilogram of fuel consumed are calculated assuming the fuel has 860 grams of carbon per kilogram of fuel. The following is an explanation of the data fields found in this database:

License	Vehicle license plate.
State	State license plate issued by.
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Co_co2	Measured carbon monoxide / carbon dioxide ratio
Co_err	Standard error of the CO/CO_2 measurement.
Hc_co2	Measured hydrocarbon / carbon dioxide ratio (propane equivalents).
Hc_err	Standard error of the HC/CO_2 measurement.
No_no2	Measured nitric oxide / carbon dioxide ratio.
No_err	Standard error of the NO/CO_2 measurement.
So2_co2	Measured sulfur dioxide / carbon dioxide ratio.
So2_err	Standard error of the SO_2/CO_2 measurement.
Nh3_co2	Measured ammonia / carbon dioxide ratio.
Nh3_err	Standard error of the NH_3/CO_2 measurement.
No2_co2	Measured nitrogen dioxide / carbon dioxide ratio.
No2_err	Standard error of the NO_2/CO_2 measurement.
Opacity	IR Opacity measurement, in percent.
Opac_err	Standard error of the opacity measurement.
Restart	Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.
Hc_flag	Indicates a valid hydrocarbon measurement by a “V”, invalid by an “X”.
No_flag	Indicates a valid nitric oxide measurement by a “V”, invalid by an “X”.
So2_flag	Indicates a valid sulfur dioxide measurement by a “V”, Invalid by an “X”.
Nh3_flag	Indicates a valid ammonia measurement by a “V”, Invalid by an “X”.
No2_flag	Indicates a valid Nitrogen dioxide measurement by a “V”, Invalid by an “X”.
Opac_flag	Indicates a valid opacity measurement by a “V”, invalid by an “X”.

Max_co2	Reports the highest absolute concentration of carbon dioxide measured by the remote sensor over an 8 cm path; indicates plume strength.
Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”, and slow speed (excluded from the data analysis) by an “S”.
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Ref_factor	Reference factor.
CO2_factor	CO2 factor.
Tag_name	File name for the digital picture of the vehicle.
Exp_Date	Date that current vehicle registration expires.
Year	Model year of the vehicles chassis.
Make	Manufacturer of the vehicle.
Vin	Vehicle identification number.
County	County code where vehicle resides.
CO_gkg	Grams of CO per kilogram of fuel consumed.
HC_gkg	Grams of HC per kilogram of fuel consumed.
NO_gkg	Grams of NO per kilogram of fuel consumed.
SO2_gkg	Grams of SO_2 per kilogram of fuel consumed.
NH3_gkg	Grams of NH_3 per kilogram of fuel consumed.
NO2_gkg	Grams of NO_2 per kilogram of fuel consumed.
VSP	Vehicle specific power in kw/tonne.

APPENDIX C: Temperature and Humidity Data.

Data collected at Fullerton Municipal Airport

Peralta 2010 Temperature and Humidity Data										
Time	4/26 °F	4/26 %RH	4/27 °F	4/27 %RH	4/28 °F	4/28 %RH	4/29 °F	4/29 %RH	4/30 °F	4/30 %RH
5:53	54	93	56	83	58	87	55	40	49	63
6:53	56	87	56	83	59	84	57	32	54	57
7:53	58	81	57	80	62	65	59	29	59	44
8:53	64	65	57	80	64	52	60	27	62	38
9:53	68	57	59	75	65	49	63	23	65	29
10:53	71	53	61	72	65	49	65	22	68	32
11:53	69	57	64	63	66	47	66	19	69	29
12:53	71	53	66	59	67	42	65	28	72	24
13:53	71	53	65	61	66	43	66	29	72	20
14:53	74	48	64	63	66	43	66	32	70	25
15:53	73	48	63	68	66	40	65	37	70	21
16:53	70	53	64	65	63	45	66	31	67	26

Data collected at Daugherty Field in Long Beach

Port of LA 2010 Temperature and Humidity Data										
Time	5/3 °F	5/3 %RH	5/4 °F	5/4 %RH	5/5 °F	5/5 %RH	5/6 °F	5/6 %RH	5/7 °F	5/7 %RH
5:53	55	86	56	90	58	84	59	75	58	90
6:53	59	81	59	84	59	81	61	72	62	78
7:53	65	61	63	73	61	78	64	65	66	63
8:53	68	57	65	68	64	70	64	63	70	51
9:53	73	46	67	63	65	68	67	59	70	61
10:53	75	45	65	65	66	65	68	59	72	53
11:53	77	42	67	61	68	61	69	57	75	45
12:53	81	35	69	57	68	61	67	61	79	36
13:53	80	37	68	59	67	66	69	55	79	34
14:53	77	43	68	61	67	63	70	53	79	31
15:53	76	45	67	63	66	65	72	46	77	28
16:53	74	45	68	61	64	70	70	44	73	29

APPENDIX D: Field Calibration Record.

Peralta 2010 FEAT Calibration Factors							
Date	Time	CO	HC	NO	SO_2	NH_3	NO_2
4/26	8:20	2.06	1.86	1.64	1.75	0.87	1.49
4/26	10:25	1.88	1.71	1.56	1.57	0.93	1.31
4/26	11:40	1.73	1.60	1.37	1.41	0.95	1.17
4/27	7:40	1.96	1.72	1.63	1.86	.88	1.53
4/27	10:17	1.82	1.62	1.42	1.64	0.92	1.32
4/27	12:00	1.69	1.52	1.42	1.64	0.88	1.26
4/27	14:30	1.62	1.46	1.28	1.19	0.90	1.21
4/28	8:30	1.81	1.63	1.60	1.76	0.89	1.40
4/28	11:30	1.68	1.50	1.39	1.58	0.94	1.12
4/29	7:24	1.95	1.74	1.66	1.96	1.0	1.69
4/29	9:09	1.90	1.69	1.56	1.89	1.08	1.35
4/29	11:00	1.68	1.47	1.47	1.63	1.08	1.53
4/30	7:20	2.26	2.01	1.97	2.08	0.91	1.51
4/30	8:42	1.91	1.71	1.63	1.71	1.0	1.23
4/30	10:50	1.75	1.56	1.52	1.85	1.04	1.33

Port of LA 2010 FEAT Calibration Factors							
Date	Time	CO	HC	NO	SO_2	NH_3	NO_2
5/3	8:30	1.70	1.52	1.39	1.34	0.94	1.02
5/3	12:05	1.43	1.27	1.20	1.04	0.96	0.77
5/4	8:30	1.61	1.40	1.34	1.15	0.91	1.10
5/4	12:30	1.43	1.26	1.12	1.22	0.94	0.93
5/5	10:25	1.42	1.25	1.15	1.39	0.97	1.0
5/6	8:30	1.50	1.32	1.23	1.27	0.92	1.0
5/6	11:00	1.39	1.25	1.17	1.41	0.93	0.95
5/6	14:30	1.36	1.22	1.11	1.24	0.97	0.85
5/7	8:15	1.62	1.45	1.35	1.66	0.95	1.0
5/7	10:00	1.46	1.31	1.24	1.47	0.94	0.95
5/7	13:30	1.37	1.24	1.13	1.36	1.01	0.84

APPENDIX E: Engine Specifications and Press Releases.

News Release

Westport Sells 50 LNG Port Trucks to Southern Counties Express; Initial Order From Leading Port Trucker to Improve Air Quality in Los Angeles Basin

March 17th, 2008

VANCOUVER, BC– Westport Innovations Inc. (TSX:WPT), a global leader in alternative fuel, low-emissions transportation technologies, announced today that Southern Counties Express, Inc. (SCE) has placed an initial order for 50 Kenworth LNG T800 Class 8 trucks, representing a value of approximately US$4 million for Westport's LNG heavy-duty engines and fuel systems. The trucks are being purchased with financial support from the San Pedro Bay Ports' Clean Trucks Program, an initiative led by the Port of Los Angeles, the Port of Long Beach and the South Coast Air Quality Management District (SCAQMD).

"With funding beginning to flow for the San Pedro Bay Ports' Clean Trucks Program, SCE has stepped forward to be the first significant fleet adopter and can now realize the benefits of clean, cost-effective LNG trucks powered by Westport's high-efficiency, low-emission technology," stated Michael Gallagher, President and Chief Operating Officer of Westport. "LNG fuel for heavy-duty trucks offers cleaner operation with a domestically available fuel."

The LNG trucks were assembled at Inland Kenworth in California and are ready for deployment. The trucks are expected to commence container movement service at the Ports of Los Angeles and Long Beach (the San Pedro Bay Ports) over the next few weeks.

Brian Griley, SCE CEO added, "As one of the first port operators running clean trucks using domestic LNG fuel, Southern Counties will be making a significant contribution to the San Pedro Bay Ports' goal of reducing harmful particulate matter, NOx and greenhouse gases in the Los Angeles basin."

The Green Fleet™ division of SCE has been in the making for over two years. It is a program designed to implement alternative fuel, heavy duty trucks into SCE's fleet. The Green Fleet will begin operation with LNG trucks owned by SCE and leased to owner-operator independent contractors. The 50 new LNG trucks will complement SCE's existing fleet of approximately 150 trucks. http://www.thegreenfleet.com/index.html

Nine other Port trucking firms have also committed to the new LNG trucks in the initial port deployment. Westport expects to conclude purchase agreements with these fleets over the next few weeks now that funding approvals from the Ports and the City of Los Angeles are in place.

About Westport's LNG System for Heavy Duty Trucks
Westport's LNG system for heavy duty Class 8 trucks offers class-leading emissions, including lower greenhouse gas emissions than comparable diesel engines, and allows trucking fleets to move to lower-cost, domestically available natural gas and/or biogas. The Westport LNG system comprises LNG fuel tanks, proprietary Westport fuel injectors, cryogenic fuel pumps and associated electronic components to facilitate robust performance and reliable operation. The Westport LNG system is 2007 EPA and CARB certified to 0.8g/bhp-hr NOx and 0.01g/bhp-hr PM. Kenworth, Southern California dealer Inland Kenworth, Westport and Clean Energy Fuels received the prestigious Alternative Fuel Vehicle Institute's 2007 Industry Innovation Award for this truck product.

About the Kenworth T800 LNG Truck Specification
The Kenworth T800 is one of the most versatile trucks on the market today. This operational versatility, coupled with its legendary reliability and high resale value, gives the T800 unmatched levels of customer satisfaction. The Westport engine is fuelled with LNG - a safe, cost effective, low carbon, and low emissions fuel. The Westport LNG system is available with 400 and 450 horsepower ratings and up to 1,750 lb-ft torque for heavy duty port, freight and vocational applications. LNG fuel tanks can be configured to suit customer range requirements. Trucks are eligible for federal tax credits in the United States and may

be eligible for other state-specific emissions credits.

About Westport Innovations Inc.
Westport Innovations Inc. is a leading global supplier of proprietary solutions that allow engines to operate on clean-burning fuels such as compressed natural gas (CNG), liquefied natural gas (LNG), hydrogen, and biofuels such as landfill gas. Cummins Westport Inc., Westport's joint venture with Cummins Inc., manufactures and sells the world's broadest range of low-emissions alternative fuel engines for commercial transportation applications such as trucks and buses. BTIC Westport Inc., Westport's joint venture with Beijing Tianhai Industry Co. Ltd., manufactures and sells LNG fuel tanks for vehicles. www.westport.com

Note: This document contains forward-looking statements about Westport's business, operations, technology development or the environment in which it operates, which are based on Westport's estimates, forecasts and projections. These statements are not guarantees of future performance and involve risks and uncertainties that are difficult to predict, or are beyond Westport's control. Consequently, readers should not place any undue reliance on such forward-looking statements. In addition, these forward-looking statements relate to the date on which they are made. Westport disclaims any intention or obligation to update or revise any forward-looking statements, whether as a result of new information, future events or otherwise.

For further information, please contact:

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Director, Investor Relations
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Fax: 604-718-2001
Email: invest@westport.com
Web: www.westport.com

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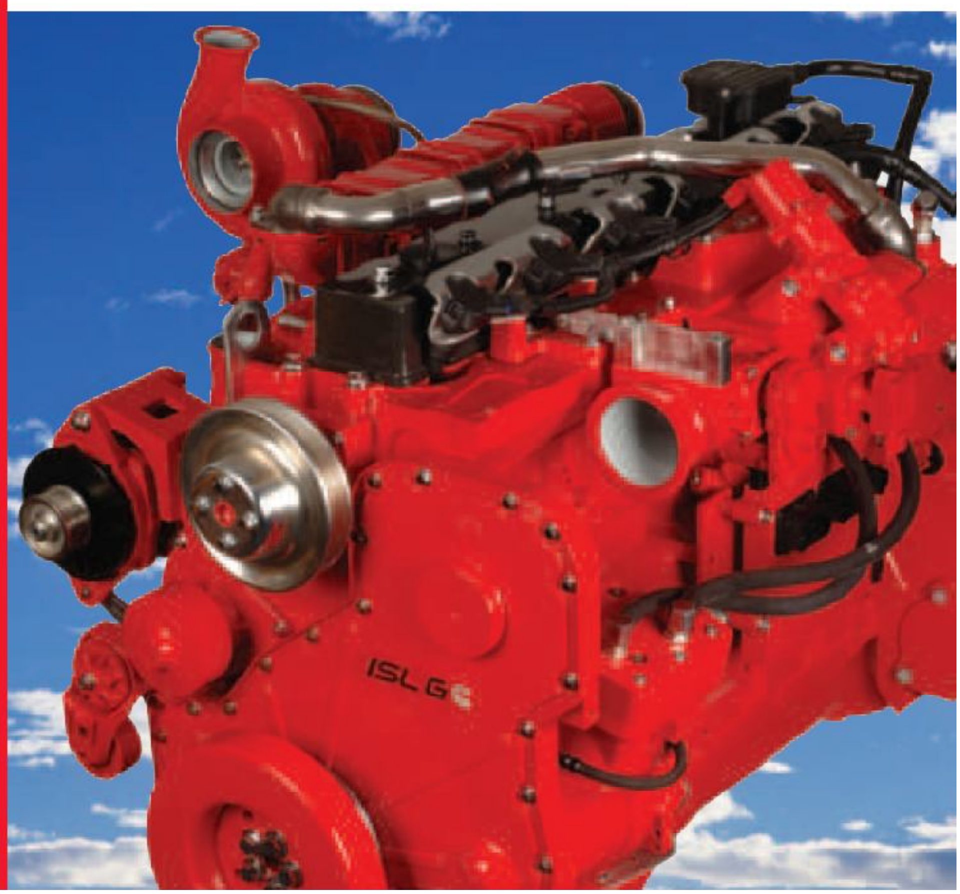
Westport

Every™ Alternative. ISL G.

Natural Gas Engines For Truck And Bus.



Natural Gas Engines For Truck And Bus.

Lower Emissions, Improved Performance, Lower Costs.

The ISL G is the newest evolution of alternative fuel engine technology, combining all the advantages of clean-burning natural gas with "no compromise" power and torque for shuttle and school bus, urban transit, vocational and medium and heavy-duty truck and tractor applications.

It combines high displacement and superior horsepower with proven wastegate turbocharger technology for impressive low-end torque and transient response, with an increase in fuel efficiency. The ISL G has met 2010 U.S. EPA and CARB emissions standards since 2007.

The ISL G engine block is shared with the rugged Cummins ISL diesel – a full-skirted block for increased rigidity and strength. The design provides superior piston ring and bearing life, improved coolant flow and targeted piston cooling for greater reliability and superior durability. Life-to-rebuild and rebuildability are the same as diesel.

Advanced Combustion Technology.

The 8.9-liter ISL G uses stoichiometric cooled Exhaust Gas Recirculation (SEGR) combustion, leveraging Cummins proven EGR technology to create a high-performance natural gas engine.

The cooled EGR system takes a measured quantity of exhaust gas and passes it through a cooler to reduce temperatures before mixing it with fuel and the incoming air charge to the cylinder.

Cooled EGR, in combination with stoichiometric combustion (the theoretical or ideal combustion process in which fuel and oxygen are completely consumed, with no unburned fuel or oxygen in the exhaust), provides significant benefits.

The use of cooled EGR (in place of large amounts of excess air used in lean burn technology) lowers combustion temperatures and knock tendency. SEGR combustion also improves power density and fuel economy vs. lean burn and traditional stoichiometric engines. Compared to previous Cummins Westport (CWI) lean burn natural gas engines, ISL G torque at idle is improved over 30% and fuel economy is improved by up to 5%.

Maintenance-Free Aftertreatment.

Another benefit of the ISL G's advanced combustion technology is SEGR combustion creates an oxygen-free exhaust, which in turn allows for the use of Three-Way Catalyst (TWC) aftertreatment. TWCs are effective, simple passive devices packaged as part of the muffler that provide consistent performance and are maintenance-free. The ISL G does not require active aftertreatment such as a diesel particulate filter (DPF) or selective catalytic reduction (SCR).

ISL G Ratings

Engine Model	Advertised HP(kW) @ RPM	Peak Torque LB-FT (N•M) @ RPM	Governed Speed
ISL G 320	320 (239) @ 2000	1000 (1356) @ 1300	2200 RPM
ISL G 300	300 (224) @ 2100	860 (1166) @ 1300	2200 RPM
ISL G 280	280 (209) @ 2000	900 (1220) @ 1300	2200 RPM
ISL G 260	260 (194) @ 2200	660 (895) @ 1300	2200 RPM
ISL G 250	250 (186) @ 2200	730 (990) @ 1300	2200 RPM

ISL G Specifications

Maximum Horsepower	320 HP	239 KW
Peak Torque	1000 LB-FT	1356 N•M
Governed Speed	2200 RPM	
Clutch Engagement Torque	550 LB-FT	746 N•M
Type	4-CYCLE, SPARK-IGNITED INLINE 6-CYLINDER, TURBOCHARGED, CAC	
Engine Displacement	540 CU IN	8.9 LITERS
Bore and Stroke	4.49 x 5.69 IN	114 x 144.5 MM
Operating Cycles	4	
Oil System Capacity	7.3 U.S. GALLONS	27.6 LITERS
Coolant Capacity	13.1 U.S. QT	12.4 LITERS
System Voltage	12 V	
Net Weight (Dry)	1625 LB	737 KG
Fuel Type	CNG/LNG/BIOMETHANE	METHANE NUMBER 75 OR GREATER
Aftertreatment	THREE WAY CATALYST (TWC)	

Fuel Capability.

The ISL G is capable of operating on compressed or liquid natural gas (CNG, LNG). The ISL G can also operate on up to 100% biomethane – renewable natural gas made from biogas or landfill gas that has been upgraded to pipeline and vehicle fuel quality. Biomethane fuel is carbon dioxide (CO_2) neutral and using it as fuel reduces vehicle greenhouse gas emissions by up to 90%.

Features And Benefits.

- Factory Built, Dedicated Natural Gas Engine – Built on the same assembly line as Cummins diesels, the ISL G shares many components and parts with Cummins L Series diesels, inheriting their renowned simplicity.
- Air/Fuel Regulation – Cummins closed-loop electronic control system based on Cummins Interact™ System. Sensors for engine parameters, including intake manifold pressure and temperature, fuel inlet pressure, knock detection, air/fuel ratio, and fuel mass flow. Electronically controlled wastegate turbocharger.
- Air Intake System – Charge air cooling reduces emissions by lowering intake manifold air temperatures.
- Accessory Belt Drive System – Self-tensioning serpentine polyvee belt accessory drive system for water pump, engine-mounted fan hub and most alternators. Gear-driven air compressor with provision for gear-driven hydraulic pump.
- Three-Way Catalyst – Required for all models. The ISL G meets U.S. EPA 2010 and California Air Resources Board standards at 0.20 g/bhp-hr of Oxides of Nitrogen (NOx) and 0.01 g/bhp-hr of Particulate Matter (PM). Meets EPA useful-life requirement and is maintenance-free.
- High-Energy Ignition System – Provides better performance and longer service intervals, improved spark plug and coil durability, plus self-diagnostics.
- High-Efficiency Lube Cooler – Lowers oil temperatures for longer engine life.
- Crankshaft – Eight counterweight, fully balanced, high-tensile-strength steel forging with induction-hardened fillets and journals for outstanding durability.
- Oil Filter – The combination full-flow and bypass oil filter improves filtration while minimizing oil filter replacement and disposal costs.
- Control System – Full drive-by-wire. New Electronic Control Module (ECM) provides full monitoring and control of engine sensors, fuel system and ignition system. Full interface capability to Cummins INSITE™ and diagnostic service tools. ECM provides Original Equipment Manufacturers (OEMs) and end users with the ability to tailor performance of the engine to fit the vehicle mission.

Electronic features include:

– Road speed governing
– Accelerator interlock
– SAE J1587/J1939 data links
– PTO control
– Cruise control
– Engine protection system

- Parts Simplicity – Enables most engine service and repair operations with common tools.
- Wastegated Turbocharger – With electronic control for precise air handling. Water-cooled bearing housing for durability.

On/Off-Highway Applications And Gearing Recommendations.

The ISL G engine is an excellent choice for medium/heavy-duty truck and tractor applications, shuttle and school buses, urban transit buses, articulated buses, and on/off-highway applications such as larger refuse and dump trucks. The high torque and broad power band of the ISL G provide excellent performance when matched to various automatic transmissions. In vocational and pickup-and-delivery applications using automatic transmissions, it is best to select the proper rear axle ratio for the vehicle's tire size and desired top road speed.

Warranty. Every Coverage.

Cummins Westport engines feature the same factory base warranty coverage as Cummins diesel engines. For transit bus and shuttle engines, a standard 2-year/unlimited-mileage/kilometers warranty with full parts and labor coverage on warrantable failures* applies. Major components are covered for 3 years/300,000 miles (482,804 km), whichever comes first.

For truck customers, full engine coverage is provided for 2 years/250,000 miles (402,336 km), whichever comes first.

Extended Coverage Plans.

For additional peace of mind, Cummins Westport offers a variety of extended coverage plans to meet every customer's need.

For full extended coverage plan details, contact your local Cummins distributor or Cummins Westport representative.

Customer Support Every Place You Need It.

Local service and warranty support as well as parts availability for all Cummins Westport products are available at any authorized Cummins facility. Cummins global network includes 550 independent and company-owned distributors with more than 5,500 parts or service locations in 160 countries.

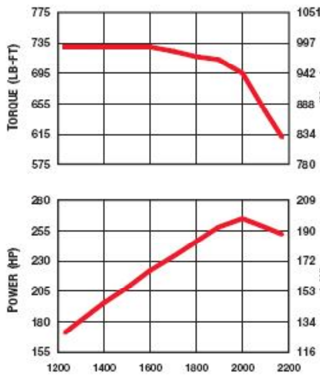
Contact our Customer Assistance Center at 1-800-343-7357.

Cummins specialists provide technical assistance, service locator and product literature 24 hours/day, 365 days/year.

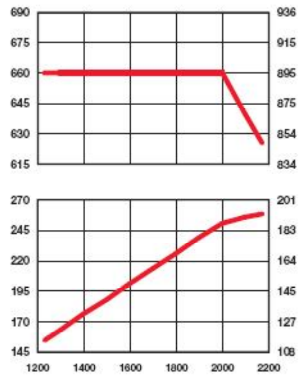
*Warrantable failures are those due to defects in materials or workmanship.

ISL G Torque And Power Curves.

250 HP/186 KW @ 2200
730 LB-FT/990 N•M @ 1300 FR 92740

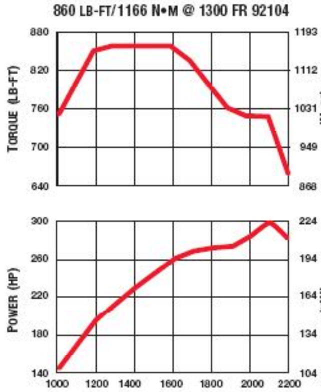


260 HP/194 KW @ 2200
660 LB-FT/895 N•M @ 1300 FR 92739

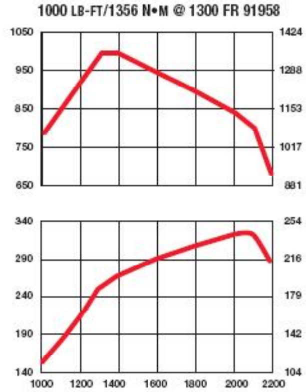


280 HP/209 KW @ 2000
900 LB-FT/1220 N•M @ 1300 FR 91959

300 HP/224 KW @ 2100
860 LB-FT/1166 N•M @ 1300 FR 92104



320 HP/239 KW @ 2000
1000 LB-FT/1356 N•M @ 1300 FR 91958



ISL G Maintenance Intervals

	Miles/Kilometers	Hours	Months
Oil and Filter	7,500 MI 12,000 KM	500	6
Fuel Filter	15,000 MI 24,000 KM	1,000	12
Coolant Filter	7,500 MI 12,000 KM	500	6
Spark Plugs	22,500 MI 36,000 KM	1,500	18
Change Coolant	30,000 MI 48,000 KM	2,000	24
Valve Adjustment	30,000 MI 48,000 KM	2,000	24

Cummins Westport is a pioneer in product improvement. Thus specifications may change without notice. Illustrations may include optional equipment.

EXPLORE EVERY ALTERNATIVE.

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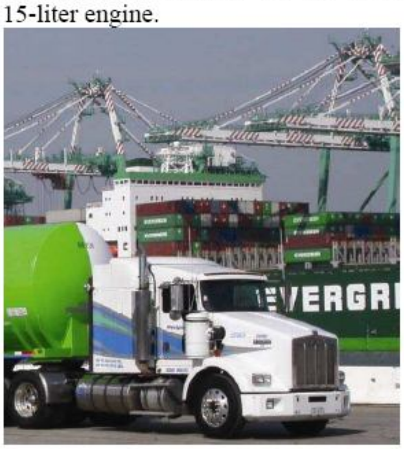
KENWORTH

Kenworth To Produce Liquefied Natural Gas Vehicles

Westport Innovations To Supply LNG Fuel System

KIRKLAND, Wash. – Kenworth Truck Company will expand its presence in the growing market for environmentally friendly, liquefied natural gas (LNG) vehicles by beginning production of Kenworth T800 LNG trucks at its manufacturing facility in Renton, Wash., in 2009. Under an exclusive agreement with Westport Innovations Inc. in Vancouver, B.C., Kenworth will use Westport's LNG fuel system technology adapted for the Cummins ISX 15-liter engine.



"The Kenworth T800, equipped with a Cummins ISX and Westport's HPDI fuel system, offers an industry-leading solution with world-class low emissions and greenhouse gases, while delivering outstanding horsepower, torque, and efficiency comparable to a diesel engine," said Bob Christensen, Kenworth general manager and PACCAR vice president. "Kenworth is recognized as a technology leader in the commercial vehicle market and the exclusive ability to offer this technology reinforces Kenworth's reputation as *The World's Best*."

"This agreement with Kenworth creates a dramatic increase in LNG truck delivery capacity and further strengthens Westport's ability to efficiently meet the significant growth in market demand for environmentally clean LNG trucks from the ports and other fleet customers," said Michael Gallagher, president and chief operating officer of Westport Innovations.

The Kenworth LNG factory installation coincides with the Ports of Los Angeles and Long Beach announcement to approve a new $1.6 billion Clean Truck Superfund. The fund will assist replacing many of the 16,800 Class 8 trucks serving the ports with LNG-powered vehicles. The ports have also introduced a new progressive ban that will remove all pre-2007 trucks by 2012. Westport's LNG fuel system is the only alternative fuel technology currently qualified for financial support under the ports' Clean Truck program.

Kenworth and Westport Innovations have previously collaborated on an aftermarket basis to equip Kenworth T800s with LNG fuel systems. These trucks are already serving the Ports of Los Angeles and Long Beach. In addition, Pacific Gas & Electric Company in San Francisco recently became the first utility in the nation to operate Kenworth T800 LNG-powered trucks.

(continued)

(continued)

Westport will open a new LNG Fuel System Assembly Center in British Columbia to support the Kenworth factory initiative and to rapidly increase production capacities of LNG fuel systems to meet growing market demand. The Westport Assembly Center will facilitate significant capability for fuel system assembly and engine conversions for delivery direct to the Kenworth plant.

About the Kenworth T800 LNG Truck Specification

The Kenworth T800 is one of the most versatile trucks on the market today. The T800 serves a variety of applications from linehaul tractors with the luxurious 86-inch Studio AeroCab® sleeper to severe service off-highway dump trucks and urban pickup and delivery vehicles. This operational versatility, coupled with its legendary reliability and high resale value, gives the T800 unmatched levels of customer satisfaction. The Westport engine is fueled with LNG - a safe, cost effective, low carbon, and low emissions fuel. The Westport LNG system is available with 400 and 450 horsepower ratings and up to 1,750 lb-ft torque for heavy duty port, freight, and vocational applications. LNG fuel tanks can be configured to suit customer range requirements. Trucks are eligible for federal tax credits in the United States and may be eligible for other state-specific emissions credits.

About Westport's LNG System for Heavy Duty Trucks

Westport's LNG system for heavy duty Class 8 trucks offers class-leading emissions, including lower greenhouse gas emissions than comparable diesel engines, and allows trucking fleets to move to lower-cost, domestically available natural gas and/or biogas. The Westport LNG system comprises LNG fuel tanks, proprietary Westport fuel injectors, cryogenic fuel pumps and associated electronic components to facilitate robust performance and reliable operation. The Westport LNG system is 2007 EPA and CARB certified to 0.8g/bhp-hr NOx and 0.01g/bhp-hr PM. Kenworth, Southern California dealer Inland Kenworth, Westport and Clean Energy Fuels received the prestigious Alternative Fuel Vehicle Institute's 2007 Industry Innovation Award for this truck product.

About Kenworth Truck Company

Kenworth Truck Company, a division of PACCAR Inc, is a leading manufacturer of heavy and medium duty trucks. Kenworth was the recipient of the 2007 J.D. Power and Associates awards for Highest in Customer Satisfaction for Over The Road, Pickup and Delivery and Vocational Segment Class 8 trucks. Kenworth's home page is www.kenworth.com.

About Westport Innovations Inc.

Westport Innovations Inc. is a leading global supplier of proprietary solutions that allow engines to operate on clean-burning fuels such as compressed natural gas (CNG), liquefied natural gas (LNG), hydrogen and biofuels such as landfill gas. Cummins Westport Inc., Westport's joint venture with Cummins Inc., manufactures and sells the world's broadest range of low-emissions alternative fuel engines for commercial transportation applications such as trucks and buses. BTIC Westport Inc., Westport's joint venture with Beijing Tianhai Industry Co. Ltd., manufactures and sells LNG fuel tanks for vehicles. www.westport.com.

NATURAL GAS ENGINE AND VEHICLE RESEARCH & DEVELOPMENT

FreedomCAR

Development of the High-Pressure Direct-Injection ISX G Natural Gas Engine

PROJECT IMPACT

This project developed the heavy-duty ISX G natural gas engine with advanced emission reduction strategies, which demonstrated oxides of nitrogen (NO_x) emissions of 0.6 g/bhp-hr and diesel-like thermal efficiency. By 2010, the U.S. Environmental Protection Agency (EPA) will require heavy-duty engine NO_x emissions of 0.2 g/bhp-hr or less (Figure 1). The technology developed in this project may help heavy-duty natural gas engines meet the 2010 requirements while being cost competitive with diesel engines. It is anticipated that this would lead to more extensive use of natural gas vehicles, resulting in reduced petroleum consumption.

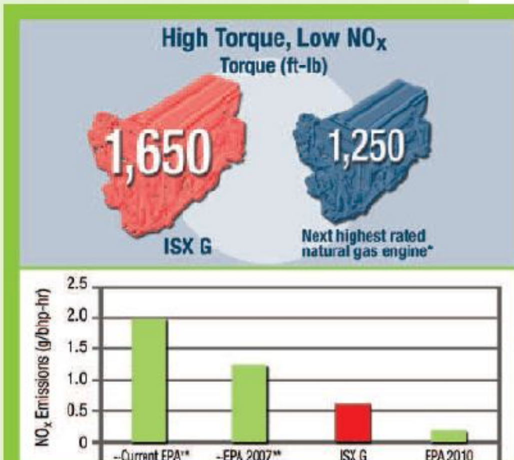


Figure 1. Demonstrated Torque and NO_x Emissions of the ISX G Engine Developed in this Project

* This statement is based on natural gas engines listed in the 2004 U.S. Department of Energy *Heavy Vehicle and Engine Resource Guide*. To obtain this document, visit the Alternative Fuels Data Center at www.*eere.energy.gov/cleancities/afdc*.

** This is an interpretation of the EPA NO_x standard. For more information on heavy-duty engine emission standards, visit www.*epa.gov*.

PROJECT GOALS

Natural gas is a domestically available resource. The U.S. Department of Energy supports natural gas vehicle R&D through its FreedomCAR and Vehicle Technologies (FCVT) Program to help the United States reduce its dependence on imported petroleum and to pave the way to a future transportation network based on hydrogen. Natural gas vehicles can also reduce emissions of regulated pollutants compared with diesel vehicles.

This project was part of the Next Generation Natural Gas Vehicle activity, which is supported by the FCVT Program, the South Coast Air Quality Management District, and the California Energy Commission. One goal of this activity is to develop advanced, commercially viable, medium- and heavy-duty natural gas engines and vehicles that will meet EPA 2007/2010 heavy-duty emission levels before 2007.

The goal of this project was to demonstrate prototype engine and vehicle technologies capable of reduced exhaust emissions and competitive operating costs for heavy-duty natural gas vehicle applications. Specific targets included the following:

- 1,650 ft-lb peak torque
- 450 hp rated power
- 40% peak thermal efficiency
- 0.5 g/bhp-hr NO_x emissions
- 0.1 g/bhp-hr particulate matter (PM) emissions.

THE HIGH-PRESSURE DIRECT-INJECTION SYSTEM

The project was led by DOE's National Renewable Energy Laboratory (NREL), Cummins, Inc., and Westport Innovations, Inc. The 15L ISX G engine is a Cummins ISX diesel engine modified to use the Westport-Cycle™ high-pressure direct-injection (HPDI™) fuel system. In this system, natural gas is delivered to the engine at high pressure along with a small amount of diesel fuel that ignites the natural gas in a compression-ignition (diesel) cycle. This enables the engine to retain the efficiency advantage of compression-ignition while consuming natural gas as its primary fuel. In this project, an ISX G engine was fitted with emission reduction equipment, calibrated, and tested over steady-state and transient cycles.

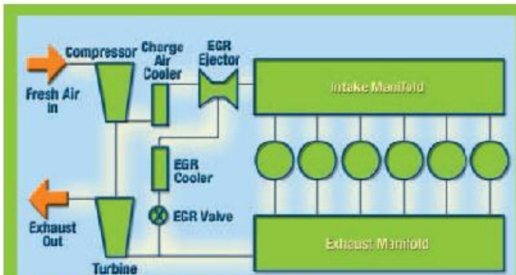


Figure 2. High-Pressure EGR Loop Schematic

Note: The final configuration included a turbine and compressor specifically designed for natural gas operation and two EGR coolers.

EMISSION REDUCTION STRATEGIES

The ISX G engine was equipped with a high-pressure exhaust gas recirculation (EGR) loop, which included a variable geometry turbocharger (VGT), EGR valve, and EGR cooler (Figure 2). In this EGR system, part of the exhaust gas is taken directly from the exhaust manifold and passed through an EGR cooler before being reintroduced into the intake air and back into the engine. The recirculated exhaust gases absorb some of the energy released during combustion of the fuel. This decreases peak combustion temperature, the most critical factor favoring high NO_x formation. The EGR fraction also displaces fresh oxygen, making less available for combustion and thus reducing the probability of interaction between nitrogen and oxygen atoms even under lean conditions.

The engine was further modified to include a smaller trim VGT compressor and second EGR cooler to enable the higher EGR rates needed to achieve the low-NO_x emission target. The second EGR cooler was installed in series with the original; this demonstration configuration is not yet practical for installation in a vehicle. A platinum/palladium oxidation catalyst was used to reduce nonmethane hydrocarbons, carbon monoxide, and PM emissions.

ENGINE CALIBRATION AND TESTING

The ISX G engine was initially calibrated and tested over the ESC 13-mode and AVL 8-mode steady-state tests, then fine-tuned for the transient Federal Test Procedure (FTP). The FTP is a 20-minute test that simulates city and highway driving and is used by the EPA to certify heavy-duty engines. The objective of the calibration and testing was to reduce NO_x emissions as much as possible without greatly increasing PM emissions and fuel consumption. Parameters such as pilot diesel and natural gas fuel quantities and timing, fuel pressures, and EGR fractions were varied to achieve optimization.

RESULTS AND CONCLUSIONS

Table 1 shows results obtained over the ESC and FTP. This project showed that the HPDI natural gas fueling system, a second EGR cooler, a smaller trim VGT compressor, and an oxidation catalyst enable significant emissions reductions on the ISX engine platform. Testing and modeling results also indicated that several untried hardware changes could improve performance and emissions. These are detailed in the full project report (see Related Publications and Web Sites below).

Table 1. ISX G Emission Test Results

	ESC 13-mode	FTP
Peak torque	N/A	1,650 ft-lb
Rated power	N/A	450 hp
Thermal efficiency (average)	36.1%	34.1%
Thermal efficiency (peak)	39.5%	N/A
NO_x (g/bhp-hr)	0.36	0.6
PM (g/bhp-hr)	0.04	0.03
THC (g/bhp-hr)	2.28	5.0
NMHC (g/bhp-hr)	0.20	Not measured
Methane (g/bhp-hr)	2.08	Not measured
Natural gas substitution*	94%	Not measured

NMHC—nonmethane hydrocarbons; NO_x—oxides of nitrogen; PM—particulate matter; THC—total hydrocarbons.
* Proportion of energy provided by natural gas, with remainder provided by diesel.

RELATED PUBLICATIONS AND WEB SITES

The report *Development of the High-Pressure Direct-Injected, Ultra Low-NO_X Natural Gas Engine*, which describes this ISX G project in detail, is available from the Alternative Fuels Data Center at *www.eere.energy.gov/cleancities/afdc*. Hard copies are available from the National Alternative Fuels Hotline at 1-800-423-1363 or *hotline@afdc.nrel.gov*. The Next Generation Natural Gas Vehicle activity is part of DOE's Natural Gas Vehicle Technology Forum. For more information, visit *www.nrel.gov/vehiclesandfuels/ngvtf*.

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