California Environmental Protection Agency

Air Resources Board

Cargo Handling Equipment
Yard Truck Emission Testing

Stationary Source Division
Emissions Assessment Branch

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Disclaimer

The ARB acknowledges that the emissions test results described herein by no means invalidate the United States Environmental Protection Agency and the ARB emissions certifications of the engines tested. The emission test results presented in this study are from vehicle chassis testing utilizing a modified 8-mode steady-state test cycle, similar to the U.S. EPA and the ARB off-road C1 test cycle.

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I. Summary

The California Air Resources Board (ARB or Board), along with the Port of Los Angeles (POLA) and Pacific Merchant Shipping Association (PMSA), funded a testing program to obtain information on the baseline emissions and promising control technologies for yard trucks at port and intermodal rail yards. Emission testing was performed on eight yard trucks, with the test matrix designed to represent the makeup of the existing fleet. Seven were equipped with engines manufactured by Cummins, and one was equipped with an engine manufactured by Caterpillar. The purpose of the emissions testing program was to:

- evaluate the effectiveness of using emulsified diesel,
- compare newer yard trucks equipped with diesel on-road and off-road certified engines,
- test alternatively fueled liquefied petroleum gas (LPG or propane) and liquefied natural gas (LNG) yard trucks, and
- evaluate the effectiveness of DOC retrofitted yard trucks.

The test fleet contained a variety of model years, yard trucks equipped with both on-road and off-road engines, and different fuels (CARB diesel, emulsified diesel, LNG, and LPG). Table 1 shows the yard truck test fleet and fuel matrix.

Table 1. Yard Truck Engine Test Fleet

Yard Truck Engine Model Year	Certification Standard	Engine Make/Model	Fuel*	After treatment	Test Date
2000	Off-road	Cummins 5.9L 6BT	CARB Diesel and Emulsified Diesel	None	5/19/05 5/20/05
1997	On-road	Cummins 8.3L 6CT	CARB Diesel and Emulsified Diesel	None	6/13/05
2001	Off-road	Cummins 8.3L 6CT	CARB Diesel and Emulsified Diesel	None	5/17/05 5/18/05
2004	Off-road	Cummins QSB 5.9L	CARB Low Sulfur Diesel	None	4/28/05
2004	On-road	Cummins ISB 5.9L	CARB Low Sulfur Diesel	None	4/29/05
2005	On-road	Caterpillar C7 7.2L	CARB Diesel	Diesel Oxidation Catalyst	3/15/06
2004	On-road	Cummins Westport B LPG Plus 5.9L	LPG	OEM 2 Way Catalyst	6/10/05
2005	On-road	Cummins Westport C Gas Plus 8.3L	LNG	OEM 2 Way Catalyst	3/14/06 5/24/06 5/25/06

To directly compare the engine emission levels in an off-road duty cycle, all testing was done using a steady-state 8-mode test cycle, similar to ARB's non-road C1 certification cycle. However, due to chassis dynamometer limitations and vehicle road speed governing limits, the intermediate modes representing engine test speeds were modified relative to those specified in the C1 test cycle. Modal data are presented and C1 test cycle weighted emission factors (C1 E_{mf}) were calculated for each vehicle test. The detailed emission testing results are included in Section V of this report.

In-use Yard Truck Testing with CARB Diesel and Emulsified Diesel

Results of the baseline testing of the three oldest model year (MY) yard trucks (1997, 2000, and 2001) indicate that there can be a significant variation in emission factors for particulate matter (PM) between the yard trucks when tested on California vehicular (CARB) diesel. Between the two Cummins 8.3 liter (L) models, the 1997 MY engine had lower modal emissions (as shown in the individual modal data) for total oxides of nitrogen (NOx) and PM than the 2001 MY. The differences in emissions may have been because the 1997 8.3L engine was manufactured to on-road standards while the 2001 MY 8.3L engine was manufactured to off-road standards. Comparison of the 2000 MY B5.9L and the 2001 MY C8.3L weighted emission factors also showed significantly different emission levels when operated on CARB diesel fuel, even though both engines were manufactured to the same off-road standards.

Comparison testing on these same yard trucks operating with an emulsified diesel relative to CARB diesel showed an overall decrease in NOx emission factors, ranging from 18 to 22 percent, and PM emission factor reductions ranging from 17 to 53 percent.

While emulsified diesel can provide significant reductions in NOx and PM of up to 22 percent and 53 percent respectively, much higher reductions are achieved by replacing the older yard trucks with new yard trucks equipped with commercially available on-road certified diesel engines. Replacement with a 2005 MY or 2006 MY yard truck equipped with an on-road engine can result in reductions in NOx and PM of up to 70 percent. In 2007, when the on-road heavy duty diesel engine standards become more stringent, the reductions will be on the order of 83 to 97 percent for NOx and 98 percent for PM, compared to the yard truck equipped with an off-road 2001 MY 8.3L Cummins engine.

Yard Trucks Equipped with Diesel On-road and Off-road Certified Engines

Comparisons between the yard trucks equipped with the 2004 on-road certified Cummins ISB (5.9L electronically controlled engine) and the 2004 off-road certified Cummins QSB (5.9L electronically controlled engine) using CARB low-sulfur diesel (less than 15 parts per million (ppm) sulfur) indicated that the on-road ISB equipped yard truck had lower emissions for NOx and PM. NOx emissions were 56 percent lower, and PM emissions were 28 percent lower for the on-road ISB equipped yard truck compared to the off-road QSB equipped yard truck.

Lower emissions from the yard truck equipped with the certified on-road engine was expected due to the more stringent ARB and U.S. EPA standards for on-road heavy duty diesel engines compared to off-road engine standards for the same model year. The reductions in emission levels will be even greater in 2007 when the on-road engine standards provide up to a 98 percent decrease in NOx and PM emissions relative to a comparable off-road engine of the same model year. (ARB, 2005)

Yard Truck Equipped with a Diesel On-road Certified Engine and DOC

While not originally included in the test plan, ARB tested a yard truck equipped with a Caterpillar C7 on-road certified diesel engine with an after treatment diesel oxidation catalyst (DOC) using CARB diesel (approximately 120 to 150 ppm sulfur). The results showed low PM and NOx emission levels. While the results are not directly comparable to the ISB and QSB equipped yard trucks because of differences in test fuels, engine makes, and exhaust treatments, the emissions levels for the Caterpillar C7 on-road certified engine and DOC configuration are lower than any of the off-road engines tested and similar in magnitude to the on-road ISB emission levels.

LPG and LNG Fueled Yard Trucks

In addition to the diesel-fueled yard trucks, tests were completed with LNG and LPG fueled yard trucks, both with on-road certified engines. Emission testing on the Cummins Westport LPG fueled yard truck indicated that the NOx emission factor was significantly higher for the LPG yard truck than the ISB (on-road) equipped yard truck operating on CARB low-sulfur diesel. PM levels were significantly lower for the LPG truck, relative to the ISB equipped yard truck.

As expected, the results of emission testing on the LNG yard truck indicated that PM levels were significantly lower compared to the yard truck with the diesel-fueled ISB engine. However, NOx emission levels were significantly higher than anticipated for the LNG yard truck relative to the diesel-fueled ISB equipped yard truck. A preliminary investigation by ARB, Cummins, and Cummins Westport staff indicated that low primary fuel pressure fault codes were recorded on the electronic control module (ECM) during both the LNG yard truck testing and terminal operation. Cummins and Cummins Westport staff were concerned that operation and testing under low primary fuel pressure fault conditions may have impacted the NOx emission levels negatively.

Significant upgrades are currently being made to the LNG yard truck's off-engine (vehicle chassis-mounted LNG fuel storage and delivery) fuel system to try to correct the low primary fuel pressure fault conditions. Further testing is planned to determine if the fuel delivery pressure problems resulted in the higher than expected NOx levels.

II. Background

Cargo handling equipment at ports and intermodal rail yards are a significant contributor of diesel PM and NOx emissions. The most common type of cargo handling equipment is the yard truck which is designed for moving cargo containers. (ARB, 2005) Containers are loaded onto the yard truck chassis by other container handling equipment, such as rubber-tired gantry cranes, top picks, or side picks, and they are unloaded the same way. Yard trucks are used to move containers and empty chassis to and from the various pieces of cargo handling equipment that receive and distribute containers.

Yard trucks are also known as yard goats, utility tractor rigs (UTRs), hustlers, yard hostlers, and yard tractors. Yard trucks are very similar to heavy-duty on-road truck tractors, but the majority of the port and intermodal yard trucks in California operate off-road, and are equipped with off-road engines. While most yard trucks are diesel-fueled, there are some that are powered by LPG, compressed natural gas (CNG), and LNG. Emulsified diesel fuel has also been used as an alternative to diesel fuel to support voluntary emission reduction programs. Yard trucks have a horsepower (hp) range of about 150 hp to 250 hp, with most being around 175 hp to 200 hp. There are approximately 2,300 yard trucks at California's ports and intermodal rail yards.

There are a number of potentially effective emission control strategies for off-road yard trucks to reduce diesel PM and NOx. The options that have shown the most potential are:

1) purchasing yard trucks with on-road certified engines;
2) using alternative fuels such as propane or natural gas;
3) using alternative diesel fuels such as emulsified diesel; and
4) installing aftertreatment systems such as diesel oxidation catalysts (DOCs).

To date, diesel particulate filter (DPF) technology has not been applied to yard trucks. The main reason for this is a concern that the engine exhaust operating temperatures may not be high enough for passive diesel particulate filters because of the duty cycle. The 2007 certified on-road diesel engines will include DPFs but will likely utilize active regeneration, which will heat the exhaust gas by auxiliary means when exhaust temperatures are not high enough to support passive regeneration.

To gather additional data on the operation of yard trucks and the emissions impacts of diesel PM control and NOx control strategies for port and intermodal yard trucks, ARB, along with POLA and PMSA, funded an emissions testing program. The purpose of the program was to:

- perform chassis emission testing on in-use yard trucks to measure baseline emission levels; and
- perform chassis emission testing to evaluate the effectiveness of promising control strategies such as on-road engines, alternative fuels, emulsified diesel, and DOC retrofits.

This report includes a summary of the emission testing, a description of the yard truck equipment and test fuels, the test results, and the preliminary findings.

Emission testing was performed by the University of California, Riverside, Bourns College of Engineering, Center for Environmental Research & Technology (UCR CE-CERT) under the direction of Wayne Miller, Ph.D.

III. Emission Testing

Emission Measurements

Emissions were analyzed for PM, total hydrocarbons (THC), carbon dioxide (CO_2), carbon monoxide (CO), and NOx per International Organization for Standardization Reciprocating Internal Combustion Engines-Exhaust Emission Measurement (ISO 8178) Parts 1, 2, and 4. (ISO 8178, 1996) Although they are a regulated pollutant, non methane hydrocarbons (NMHC) were not measured in this study. Because of the potential for THC from LNG to have a large fraction of methane, we have not attempted to compare or draw any conclusions concerning the THC emissions among the various vehicles tested. We have, however, provided the THC emissions data in Appendix 1. Exhaust analysis of the gaseous components was performed using the continuous measurement methods listed in Table 2.

Table 2. ISO 8178 Recommended Continuous Gaseous Sampling Analyzers

Gaseous Pollutant	Ambient Level Sampling Per ISO 8178
NOx	Chemiluminescence
CO	Non-dispersive infrared (NDIR)
CO2	Non-dispersive infrared (NDIR)
THC	Flame ionization detector (FID)

Emission testing was performed using full-flow constant volume sampling (CVS) per ISO 8178. In the CVS method, the system is configured such that the full engine exhaust enters the primary tunnel where it is diluted with air to maintain a constant total flow rate (air + exhaust) under all running conditions. Samples for continuous gas phase measurements are drawn from the primary dilution tunnel. A sample for particulate measurement is drawn from the primary tunnel into a smaller secondary dilution tunnel where it is further mixed with air and passed through filters at a fixed mass flow ratio and at a temperature of 47+5 degrees Celsius (ºC). Samples for continuous gas phase measurements are drawn from the primary dilution tunnel. The volumetric flow rates of the dilution air and diluted exhaust gas for the primary and secondary tunnels are measured, along with temperatures and pressures, allowing computation of the total mass flow rate of exhaust and mass emission rates of the sampled components.

Test Cycles

Mass emission rates were measured at steady-state conditions for specified speeds and loads developed for off-road engine applications as listed in ISO 8178 Part 4. In-use testing was not performed due to potentially large variations in the test duty cycle, difficulties sampling PM in transient in-use testing, test repeatability, and difficulty establishing brake specific engine test loads.

The C1 steady state cycle includes a set of modes, each with a specified torque, speed, and weighting factor. For a given test cycle, a weighted emission factor was calculated using weighted modal emission mass rates, divided by a weighted modal wheel horsepower value. For this testing, ARB's 8-mode C1 test cycle was selected since it is similar to the test cycle used for non-road (off-road) U.S. EPA engine certification. ARB evaluated performing in-use testing by sampling emissions while the yard trucks were performing cargo handling operations at the terminals. ARB staff believes that there would be too much variation in an in-use driving cycle to compare emission levels between the different yard truck engines. Therefore, ARB selected a vehicle chassis dynamometer test cycle to provide better repeatability. Table 3 shows the torque, speed, and weighting factors for the steady state 8-mode C1 test cycle. The chassis testing was performed using a vehicle chassis dynamometer, leased from Johnson Power Equipment of Riverside, California.

Table 3. Weighting Factors for C1 Type ISO 8178 Test Cycles

Mode number	1	2	3	4	5	6	7	8	9	10	11
Torque %	100	75	50	25	10	100	75	50	25	10	0
Speed	Rated speed					Intermediate speed					Low idle
C1 Weighting Factor	0.15	0.15	0.15		0.10	0.10	0.10	0.10			0.15

Although U.S. EPA non-road certification is performed using direct engine testing, vehicle chassis testing was used for this program. The chassis dynamometer has distinct advantages for testing in-use vehicles. The most important advantage is that the engine did not need to be removed from the vehicle. However, with chassis testing, there are additional variables influencing the results, including variations in vehicle driveline configurations (transmissions, torque converters, rear axle ratios, tire sizes), vehicle cooling package designs, ambient conditions (humidity, temperature, and wind, which will impact total air flow to the engine), and tire tread wear. With vehicle chassis dynamometer testing, the load is applied and measured at the wheel instead of directly at the engine. Due to power losses in the vehicle drive train, the wheel horsepower is lower than engine horsepower.

The horsepower specific emission factors presented in this report are calculated using the load at the wheel (whp) instead of the brake engine load (bhp) and reported as grams per wheel horsepower hour (g/whp-hr). Therefore, the emission factors measured in this vehicle chassis-testing program are higher than those measured in direct engine testing, such as engine certification, for the same engine type. In addition, the power losses may be different for each of the vehicles, depending on the vehicle manufacturer, vehicle design, and drive-train components.

Modifications were made to the intermediate test points in the C1 test cycle (modes 6, 7, and 8) because of operational constraints of the chassis dynamometer. The water brake chassis dynamometer is designed for vehicles that typically operate at highway speeds. The dynamometer requires a minimum wheel speed to develop sufficient wheel loading. Because off-road yard trucks are governed to run at a maximum speed of 18 to 20 miles per hour, the wheel speed was too low for the dynamometer to generate the 100 percent, 75 percent, and 50 percent loads at the specified intermediate speed test points. Therefore, the yard trucks had to be operated at a higher wheel speed range to achieve the loads required for modes 6, 7, and 8, as specified in the C1 cycle. The resulting intermediate engine speed points for this test program were correspondingly higher than those intermediate speed points specified in the C1 cycle for modes 6, 7, and 8. In general, the intermediate engine speed points during the chassis testing were increased from specified speed points of 1500-1600 rpm to 1800-2300 rpm (see Appendix 1). The weighted emission factors were calculated using the modified intermediate speed points.

IV. Yard Truck Test Matrix

Emission testing was performed on eight yard trucks, with the test matrix designed to represent the makeup of the existing fleet. The purpose of the emissions testing program was to evaluate the effectiveness of using emulsified diesel, compare newer yard trucks equipped with diesel on-road and off-road certified engines, test alternatively fueled LPG and LNG yard trucks, and to evaluate the effectiveness of DOC retrofitted yard trucks.

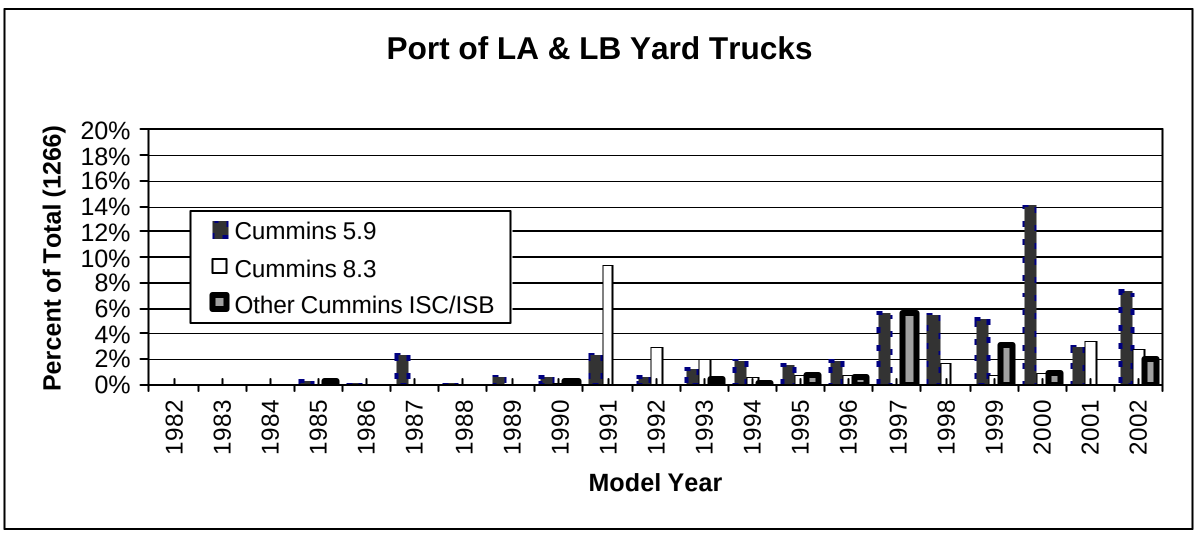
Selection of Yard Trucks for Testing

In order to develop a representative baseline for the yard truck test plan, the combined population of engines in the 2002 POLA and 2001 Port of Long Beach (POLB) baseline emission inventories were analyzed to determine the dominant engine make, model, and model year groupings. (Starcrest, 2004a and Starcrest, 2004b) Table 4 shows the number of yard truck engines by make and size for the two ports. The inventories contain a total of 1,266 yard trucks. Cummins engines represented approximately 94 percent of the inventory. Since Cummins represented the largest manufacturer grouping by far, model year distributions were developed for the two largest Cummins engine size groups, 5.9L and 8.3L. This distribution is shown in Figure 1.

Table 4. The Number of Yard Truck Engines by Make and Engine Size for POLA and POLB

Yard Truck Engine Make/Size	Total Number	Percent of Total
Cummins 5.9 liter	687	54%
Cummins 8.3 liter	331	26%
Other Cummins	180	14%
Caterpillar (all models)	3	<1%
Detroit Diesel (all models)	57	5%
Other Makes	8	1%
Total	1266	100%

Figure 1. Cummins Model Years Breakdown



Distribution is based on POLA 2001 and POLB 2002 Inventories (Starcrest, 2004a and Starcrest, 2004b).

The Cummins 5.9L engine size is the most common yard truck engine in service at the two ports, representing 54 percent of the yard truck engine population. Based on the model year breakdown for the Cummins 5.9L engines, the 2000 MY is the most common model year (14 percent of the total). Model Year 2002 is the next most common 5.9L engine size at 9 percent of the total. These two model years represent approximately 21 percent of the total yard truck inventory for the two ports. The Cummins 8.3L engine group represents the second largest engine category at 26 percent of the yard truck inventory. The most common Cummins 8.3L engine at 9 percent of the total inventory is 1991 MY. Model Year 2001 is the second most common Cummins 8.3L engine at approximately 5 percent of the inventory. These four engine makes and model years represent 37 percent of the total inventory.

Table 5. Dominant Inventory Groupings for Baseline Selection

Cummins Engine	Model Year	Percent of Yard Truck Inventory
5.9 L	2000	14
5.9 L	2002	9
8.3 L	1991	9
8.3 L	2001	5

The model year information shown in Table 5 was used to guide the selection of the baseline test vehicles. However, two changes were made in developing the final test matrix. First, a yard truck equipped with a 1997 MY Cummins 8.3L engine was substituted for the 1991 MY yard truck, since 1991 trucks were no longer available due to the fleet turnover between the inventory dates and 2005. After the 1991 MY group, the 1997 MY was the next largest group. Second, since the 2002 MY Cummins 5.9L was within the same off-road engine tier (Tier 1) and similar in design to a 2000 MY, only the 2000 MY was tested.

In addition to the yard trucks selected to represent the in-use inventory, the test matrix included yard trucks equipped with newer on-road and off-road certified diesel-fueled engines, alternative fueled engines, and exhaust aftertreated engines. The final test matrix is shown in Table 6. The test matrix lists the yard truck engine type (make, model, rated speed, and horsepower), the yard truck test identification, the engine model year, and the type of fuel used during testing. A description of the CARB diesel fuels and emulsified diesel fuel used in the testing is shown in Table 7. The chemical analysis and physical properties for the low sulfur diesel is shown in Appendix 2 and is listed as CARB certified ultra low sulfur diesel (ULSD). The composition of gaseous samples of vaporized LNG is listed in Appendix 3.

Table 6. Yard Truck Test Matrix

Engine Type (Rated speed/hp)	Yard Truck Identification	Model Year	CARB Diesel	LS Diesel	Emulsified Diesel	Alt. Fuel
Cummins 5.9L 6BT (2200 rpm/174 Hp)	YT1	2000	1		1	
Cummins 8.3L 6CT (2200 rpm/210 hp)	YT2	1997	1		1	
Cummins 8.3L 6CT (2200 rpm/215 hp)	YT3	2001	1		1	
2004 Off-Road Engine Cummins QSB (2500 rpm/173 hp)	YT4	2004		1		
2004 On-Road Engine Cummins ISB (2300 rpm/245 hp)	YT5	2004		1		
2005 Caterpillar C7 after treated with a DOC (2400 rpm/210 hp)	YT6	2005	1			
Cummins Westport B LPG Plus 5.9L Propane Fueled Engine with OEM-2 way Catalyst (2600 rpm/185 hp)	YT7	2004				1 (LPG)
Cummins Westport C Gas Plus 8.3L LNG Fueled Engine with OEM-2 way Catalyst (2400 rpm/280 hp)	YT8	2005				1 (LNG)

Table 7. Description of CARB Diesel and Emulsified Diesel Fuels Used in Yard Truck Testing

Fuel	Description
CARB Diesel	Commercially available California vehicular (CARB) Diesel (approximately 120 to 150 ppm sulfur) fuel that meets the specifications for sulfur and aromatics as defined in Title 13, California Code of Regulations (CCR) sections 2281-2282.
CARB Low-Sulfur Diesel (LS Diesel)	Commercially available California vehicular (CARB) Diesel (15 ppm sulfur or less) fuel that meets the specifications for sulfur and aromatics as defined in Title 13, California Code of Regulations (CCR) sections 2281-2282.
Emulsified Diesel	Chevron Proformix™ is a water emulsified diesel fuel that consists of a blend of water, conventional diesel fuel (meeting the specifications of CARB diesel fuel), and an additive package, utilizing Lubrizol's PuriNOx™ technology.

In-use Yard Truck Testing with CARB Diesel and Emulsified Diesel

The three fleet-representative in-use yard trucks (YT1, YT2, and YT3) were tested using commercially available CARB Diesel (approximately 120 to 150 ppm sulfur) fuel that meets the specifications defined in Title 13, California Code of Regulations (CCR) sections 2281-2282. The in-use yard trucks were also tested with water-emulsified diesel to evaluate the impact of voluntary emission reduction programs. Water-emulsified diesel fuel was developed to reduce both NOx and PM.

The emulsified diesel, Chevron Proformix™, is a water emulsified diesel fuel that consists of a blend of water, conventional diesel fuel, and an additive package, utilizing Lubrizol's PuriNOx™ technology. Small amounts of the additive package are added to the fuel to maintain the emulsion, enhance cetane and lubricity, inhibit corrosion, protect against freezing, and prevent foaming. The water is suspended in droplets within the fuel lowering PM emissions by creating a leaner fuel environment in the engine. Also, the emulsified fuel creates a cooling effect in the combustion chamber, thereby decreasing cylinder temperatures, resulting in lower NOx emissions.

Yard Trucks Equipped with Diesel On-road and Off-road Certified Engines

A direct comparison was performed between yard trucks equipped with a current (2004 MY) electronically controlled Cummins off-road engine (QSB 5.9L) and a current (2004 MY) electronically controlled Cummins on-road engine (ISB 5.9L). Both of these engines were certified engines. The on-road engine was certified with a transient on-highway test procedure. The off-road engine was certified using a non-road 8-mode (C1) steady state test procedure. To directly compare the emission levels of both yard trucks in an off-road application, both yard trucks were tested using the modified non-road 8-mode C1 (modified) steady state test procedure described previously. CARB low-sulfur diesel was used for this component of the testing to best represent proposed regulatory control strategies.

Yard Truck Equipped with an On-road Certified Engine and DOC After treatment

Emission testing was performed on a yard truck equipped with a 2005 MY diesel on-road certified Caterpillar C7 engine that had been retrofitted with a DOC. To directly compare to the emission levels of the other yard trucks in the study, the DOC retrofitted yard truck was tested using the C1 (modified) steady state test procedure described previously. CARB diesel was used for this component of the testing.

LPG and LNG Fueled Yard Trucks

Alternative fuels such as LPG, CNG, and LNG are potential options available to reduce emissions from compression ignition engines. Some cargo handling equipment applications, specifically yard tractors, are using LPG and LNG as an alternative to diesel fuel at some terminals. When comparing certification emission levels, engines using alternative fuels such as LNG, CNG or LPG have emission levels that are comparable or lower than new on-road or off-road diesel engines operating on CARB diesel. Currently, POLA has 53 LPG yard tractors in service as part of early production demonstration programs. Terminals at both POLB and POLA have a combined total of five LNG yard tractors in service as part of early production demonstration programs.

The test plan included one yard truck equipped with a 2004 Cummins Westport on-road certified LPG fueled engine and one with an on-road certified 2005 Cummins Westport LNG fueled engine (Cummins Westport is a joint venture company established by Cummins, Inc. and Westport Innovations, Inc.). As with the diesel-fueled Cummins ISB engine, these engines are certified using an on-highway transient test procedure. To directly compare to the other yard trucks tested in this program, the LPG and LNG yard trucks were tested using the C1 (modified) steady state test procedure described previously.

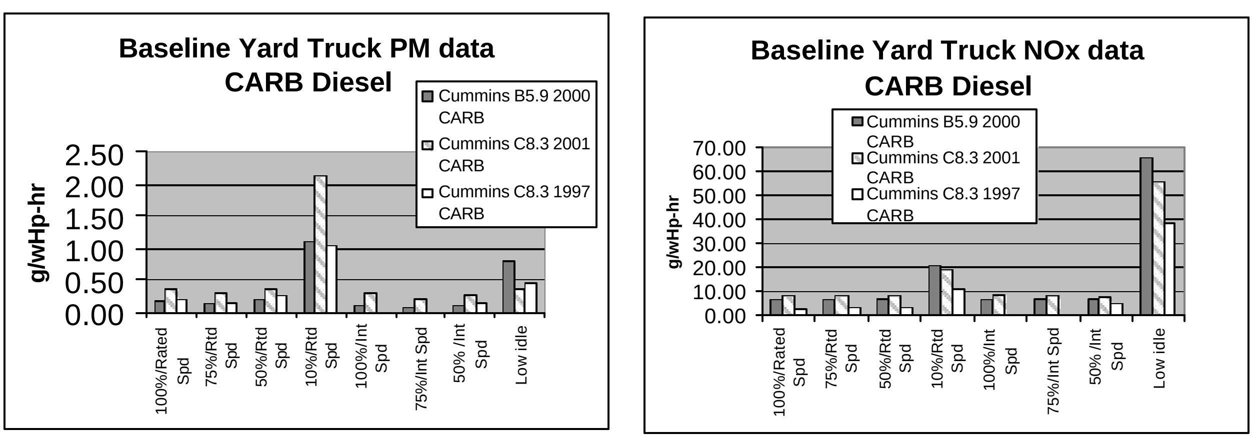
V. Results and Discussion

The results of the emission testing of the various yard trucks is provided below. Modal data for all yard trucks tested is provided in Appendix 1.

<u>In-use Yard Truck Testing with CARB Diesel and Emulsified Diesel</u>

Three yard trucks were tested with both CARB diesel and Proformix™ emulsified diesel. The yard trucks tested were equipped with a 2000 MY Cummins B5.9L off-road engine, a 2001 MY Cummins C8.3L off-road engine, and a 1997 MY Cummins C8.3L on-road engine. We were not able to test the 1997 MY Cummins C8.3L engine in modes 6 and 7 due to automatic shifting of the transmission. Therefore, we were not able to calculate corresponding C1 (modified) weighted emission factors for that vehicle. To compare modal emissions between the three yard trucks, modal values are shown in Figure 2.

Figure 2. Modal Emission Factors for Baseline Yard Truck Engine Testing with CARB Diesel



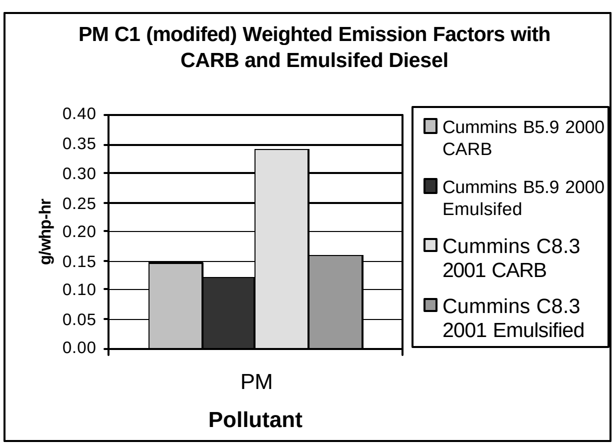
Comparison of the 2000 MY B5.9L and the 2001 MY C8.3L baseline weighted emission factors showed significantly different emission levels when operated on CARB diesel fuel. As shown in Table 8 and in Figure 3, the C1 (modified) weighted emissions for the 2000 MY B5.9L engine were 7.13 g/whp-hr and 0.15 g/whp-hr, respectively, for NOx and PM. The C1 (modified) weighted emissions for the 2001 MY C8.3L engine were 8.49 g/whp hr and 0.35 g/whp-hr, respectively, for NOx and PM. Between the two Cummins 8.3L models, the 1997 MY engine had lower modal emissions for total NOx and PM than the 2001 MY, as shown in Table 2. The differences in emissions may have been because the 1997 8.3L engine was manufactured to on-road standards while the 2001 MY 8.3L engine was manufactured to off-road standards.

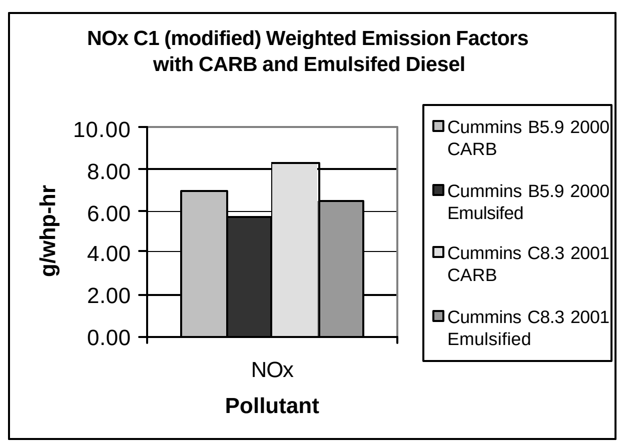
Table 8. Average Modified C1 Weighted Emission Factors for Yard Truck Engine Testing with CARB Diesel and Emulsified Diesel

Engine Type	Cummins 5.9L 6BT 2000 MY		Cummins 8.3L 6CT 2001 MY		Cummins 8.3L 6CT 1997 MY	
Fuel	CARB Diesel	Emulsified Diesel	CARB Diesel	Emulsified Diesel	CARB Diesel	Emulsified Diesel
	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
NOx	7.13	5.85	8.49	6.64	See Note 2	See Note 2
NOx % Reduction		18%		22%		See Note 2
PM	0.15	0.12	0.35	0.16	See Note 2	See Note 2
PM % Reduction		17%		53%		See Note 2

Note 1. Negative number indicates Increase in Total Hydrocarbon
Note 2. A weighted C1 emission factor could not be calculated because modes 6 and 7 were not performed due to automatic transmission shifting. See individual modal data listed in Appendix 1 for comparisons.

Figure 3. Average Modified C1 Weighted Emission Factors for Yard Truck Engine Testing with CARB Diesel and Emulsified Diesel





Emission testing of the 2000 MY B5.9L with emulsified diesel showed reductions in NOx of 18 percent and reductions in PM of 17 percent. Emission testing of the 2001 MY C8.3L with emulsified diesel showed reductions in NOx of 22 percent and reductions in

PM of 53 percent. For both engines, these reductions are relative to operation on CARB diesel fuel.

The variability in emission reductions provided by the emulsified diesel fuel seems to be dependent on engine design and baseline engine emission levels. This variation may also be influenced by test to test variation and vehicle to vehicle differences (e.g., driveline configurations, tire wear, and cooling package design). However, the results also show that for the engines tested, emulsified fuel is an effective emission reduction technology for PM and NOx.

Yard Trucks Equipped with Diesel On-road and Off-road Certified Engines

Emission testing was performed on a yard truck equipped with an electronically controlled Cummins 2004 off-road certified engine (QSB 5.9L) and a yard truck equipped with an electronically controlled Cummins 2004 on-road certified engine (ISB 5.9L), both using CARB low-sulfur diesel fuel. As shown in Table 9, the C1 (modified) weighted emissions for the QSB equipped yard truck were 5.41 g/whp-hr and 0.14 g/whp-hr, respectively, for NOx and PM. The C1 (modified) weighted emissions for the ISB equipped yard truck were 2.39 g/whp-hr and 0.10 g/whp-hr, respectively, for NOx and PM.

Table 9. Average Modified C1 Weighted Emission Factors for Yard Trucks with Off-road, On-road, and DOC Retrofitted Engines

Pollutant	Cummins 2004 5.9L QSB LS Diesel	Cummins 2004 5.9L ISB LS Diesel	Caterpillar 2005 C7 7.2L with DOC CARB Diesel
	(g/whp-hr)	(g/whp-hr)	(g/whp-hr)
NOx	5.41	2.39	2.87
PM	0.14	0.10	0.07

Comparisons between the QSB (off-road certified) equipped yard truck and the ISB (on-road certified) equipped yard truck on CARB low-sulfur diesel show that the ISB equipped truck has 56 percent lower NOx and 28 percent lower PM. These results demonstrate that the emission levels for the ISB equipped yard truck are significantly lower than the QSB equipped yard truck, when tested under the same off-road C1 (modified) test cycle. The lower emissions from the yard truck equipped with the Cummins ISB on-road certified is a direct result of more stringent ARB and U.S. EPA emission standards for on-road heavy duty diesel engines, as compared to emission standards for off-road heavy duty diesel engines for the same model years.

Yard Truck Equipped with an On-road Certified Engine and DOC After treatment

Emission testing was performed for a yard truck equipped with a 2004 on-road certified Caterpillar C7 engine and a DOC exhaust after treatment device using CARB diesel.

While this engine make and exhaust after treatment were not originally included in the test matrix and baseline (i.e., without the DOC installed) emission testing was not performed, the yard truck was tested to provide information on DOC equipped on-road engines. As shown in Table 9, the C1 (modified) weighted emissions were 2.87 g/whp-hr and 0.07 g/whp-hr, respectively, for NOx and PM.

LPG and LNG Fueled Yard Tractors

Emission testing was performed on a yard truck equipped with a 2004 MY on-road certified Cummins Westport LPG engine. As shown in Table 10, the C1 (modified) weighted emissions were 3.49 g/whp-hr and 0.01 g/whp-hr, respectively, for NOx and PM. These results indicate that NOx emissions are significantly higher for the LPG fueled yard truck, compared to the ISB equipped yard truck. However, PM is significantly lower for the LPG yard truck than any of the diesel-fueled yard trucks. Modal data for all the tests is included in Appendix 1.

The yard truck was tested on two separate occasions: two C1 (modified) test cycles in March 2006 (runs 1 and 2) and three C1 (modified) test cycles in May 2006 (runs 3, 4, and 5). During testing, the truck ran out of fuel on runs 2 and 4, and those runs were not included in the average weighted emissions.

Emission testing was also performed on a yard truck equipped with a 2005 MY on-road certified Cummins Westport 8.3L natural gas engine fueled with LNG. The yard truck was initially tested in March 2005. In addition to emission testing, the electronic control module (ECM) information was downloaded after the emission testing was completed, using Cummins' INSITE software package.

ARB staff provided the preliminary data and reviewed the preliminary test results and the ECM information with Cummins and Cummins Westport staff, since the measured NOx levels were significantly higher than anticipated. In addition to the higher than anticipated NOx levels, the ECM on the LNG yard tractor was found to have recorded 255 low fuel pressure fault code activations. As 255 fault codes is the maximum the ECM is capable of recording, the actual number of fault code instances is unknown. After reviewing the results of the initial LNG testing, staff from Cummins and Cummins Westport expressed concerns about testing results obtained while operating under conditions of low primary fuel pressure fault codes. A number of concerns were raised by Cummins and Cummins Westport staff, including:

- emission testing while the engine was operating under fault conditions;
- possible weathering of the fuel and the potential effects on emissions; and
- emission levels may have been negatively impacted by the fault conditions during engine operation.

A technical working group comprised of staff from ARB, UC Riverside, Cummins, and Cummins Westport was assembled to address the concerns. To investigate if the fuel pressure faults were occurring only during the 8-mode emission test cycle or were also occurring during normal cargo handling operations, Cummins Cal Pacific (the Southern California distributor for Cummins and Cummins Westport engines) first performed maintenance on the tested yard truck and returned the yard truck back into routine terminal service. The maintenance performed included replacing the spark plugs and oxygen sensor. They then reviewed the ECM data after three to four days of terminal operation. After reviewing the ECM data from terminal use, low primary fuel pressure fault codes were again detected even after normal terminal operation. Even though fault codes appeared in normal use after maintenance, the working group agreed to retest the yard truck in May 2006 to address the concerns raised by Cummins and Cummins Westport staff. Given that Cummins Cal Pacific performed maintenance on the yard tractor prior to the retest, and that the retest again showed higher NOx emission levels than would normally be expected, the results indicate that the maintenance and tuning of the LNG yard truck engine was not the likely cause of the higher NOx emission levels.

To investigate fuel weathering concerns, fuel samples were taken from the yard truck fueling system during the testing done in May 2006. Fuel weathering can occur if the lighter methane components are lost during storage, resulting in a higher ratio of higher molecular weight hydrocarbon species relative to methane, the primary component of LNG. Gaseous samples of vaporized LNG were taken from the yard truck fueling system after vaporization and were analyzed for composition by gas chromatography. The chemical analysis is shown in Appendix 3. The analysis showed that the methane content ranged from 92 to 99 percent, with a Wobbe Number of 1315 to 1320, well within California's motor vehicle natural gas specifications. Since the yard truck was fueled at three different fueling stations during testing, weathering at one of the fueling stations would not have impacted all of the testing. Based on the chemical analysis of the fuel samples and the use of a number of fuel sources (fueling station at POLA, POLB, and County of Riverside), ARB staff does not believe that fuel weathering is a major factor in the results.

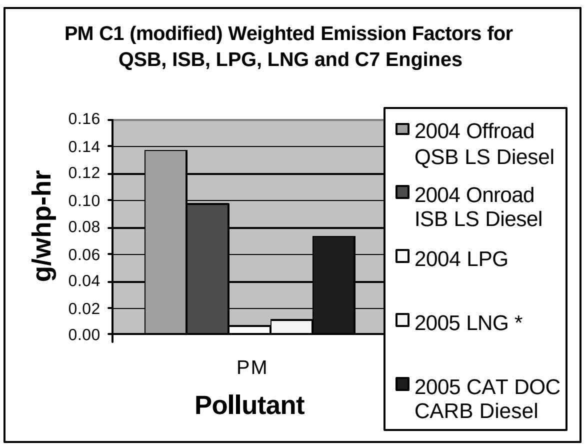
As shown in Table 10, the average C1 (modified) weighted emissions from runs 1, 3, and 5 were 4.15 g/whp-hr for NOx. The C1 (modified) weighted emissions for NOx were 4.24 g/whp-hr, 4.76 g/whp-hr, and 3.49 g/whp-hr for runs 1, 3, and 5, respectively. Due to the long test time required to sample sufficient PM on the test filters, PM was not sampled during runs 3 and 5 in order to conserve LNG. These results consistently indicate that the NOx is about two times higher for the LNG fueled yard truck, compared to the diesel-fueled ISB equipped yard truck operated on CARB low-sulfur diesel. As expected, PM is significantly lower for the LNG yard truck than either the ISB or QSB equipped yard trucks. These results are depicted in Figure 4. Modal data for all of the tests is included in Appendix 1.

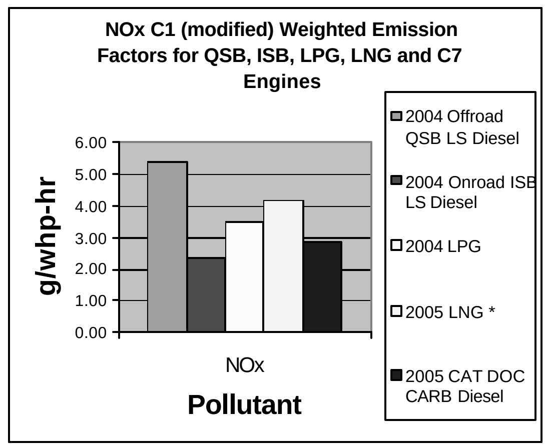
Table 10. Average C1 (Modified) Weighted Emission Factors for Yard Trucks with Off-road, On-road, LPG, and LNG Engines

Pollutant	Cummins 2004 QSB 5.9L LS Diesel	Cummins 2004 5.9L ISB LS Diesel	Cummins Westport 2004 5.9L B LPG Plus LPG	Cummins Westport 2005 8.3L C Gas Plus LNG
	(g/whp-hr)	(g/whp-hr)	(g/whp-hr)	(g/whp-hr)
NOx	5.41	2.39	3.49	4.15*
PM	0.14	0.10	0.01	0.01*

* Active low fuel pressure faults were recorded during the testing of this vehicle.

Figure 4. Average Modified C1 Weighted NOx and PM Emission Factors for Off-road, On-road, LPG, and LNG Yard Truck Engines





* Active low fuel pressure faults were recorded during the testing of this vehicle.

After reviewing the initial test results and the records from the in-service monitoring, Westport Innovations began an extensive review of the fueling system. A summary of their findings is included in Appendix 4. Based on the ECM data downloaded after the emission testing and terminal operation and the extensive analysis of the fuel system performed by Cummins Westport, ARB staff believes that the fuel delivery system in this vehicle was not operating within engine fueling specifications. The technical working group agreed that problems with the fuel delivery system may have contributed to the higher than expected NOx emissions. Through this process, Cummins Westport has committed to reevaluate and upgrade the fuel delivery system to correct the engine fueling issues. However, it is important to note that the testing performed was not the same as the testing performed by Cummins on this type of engine during its certification. As such, it is not appropriate to use these results to determine whether or not this engine is operating within its certification limits.

Further testing would be needed to determine if the upgrades being performed to the fuel system have a significant impact on the measured emission levels. Based on all the information, ARB staff has been unable to determine what effect the fuel pressure problems alone had on the NOx emissions for the LNG yard truck. ARB plans to retest the 2005 MY LNG yard truck after the upgrades to the fuel system have been completed. Since engine manufacturers are currently developing engines designed for certification to ARB's 2007 on-road heavy-duty diesel engine standards of 0.2 to 2.0 g/bhp-hr for NOx and 0.01 g/bhp-hr for PM, ARB plans to test 2007 MY yard trucks equipped with diesel and LNG on-road engines as they become available.

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(CCR Title 13, Sections 2281, 2282) Standards for Diesel Fuel, Title 13, California Code of Regulations, sections 2281, and 2282.

(ISO 8178, 1996) International Organization for Standardization. *RIC Engines-Exhaust emission measurement* ISO/DP 8178 Test Procedure, Part 1, August 15, 1996, Part 2, August 15, 1996, and Part 4, August 15, 1996.

(Starcrest, 2004a) Starcrest Consulting Group, LLC. *The Port of Los Angeles, Final Draft, Port-Wide Baseline Air Emission Inventory*; June 2004.

(Starcrest, 2004b) Starcrest Consulting Group, LLC. *2002 Baseline Emissions Inventory, Cargo Handling Equipment, Rail Locomotives, and Heavy-Duty Vehicles*; March 2004.

Appendix 1. All Yard Truck Modal Data

Ottawa Yard Truck Eng Hr/Odometer 12380.00
Cummins 2000 B5.9L
using CARB Diesel

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	100.92	2201.50	0.15	0.48	6.55	851.02	0.18
75%/Rtd Spd	68.95	2201.00	0.35	0.64	6.64	938.15	0.15
50%/Rtd Spd	45.96	2197.50	0.51	0.96	7.32	1113.45	0.19
10%/Rtd Spd	8.99	2201.50	2.68	7.99	20.56	3749.73	1.09
100%/Int Spd	126.40	1899.50	0.13	0.46	6.70	704.12	0.10
75%/Int Spd	101.42	1901.00	0.10	0.32	6.93	721.70	0.08
50% /Int Spd	67.95	1899.00	0.39	0.42	6.99	794.08	0.09
Low idle	10.09	642.50	0.45	0.88	6.56	300.20	0.08
C1 E_{mf}			0.28	0.64	6.98	865.36	0.15

Extra Data Points

Int load/IS	110.42	1552.50	0.09	0.68	7.51	656.83	0.11
<100/RS-match emuls diesel	79.94	2199.50	0.37	0.52	6.89	916.10	0.16
<100/IS-match emuls diesel	116.41	1898.00	0.16	0.37	6.93	722.75	0.09

Ottawa Yard Truck Eng Hr/Odometer 12374.00
Cummins 2000 B5.9L
using Emulsified Diesel

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	81.94	2198.50	0.44	0.65	5.28	901.69	0.17
75%/Rtd Spd	68.95	2202.50	0.26	0.82	5.35	936.97	0.14
50%/Rtd Spd	45.96	2200.00	0.65	1.33	6.02	1102.62	0.18
10%/Rtd Spd	9.49	2199.50	2.72	14.56	17.11	3455.66	0.84
100%/Int Spd	112.41	1899.00	0.20	0.37	5.69	725.27	0.06
75%/Int Spd	101.92	1897.50	0.10	0.34	5.51	720.00	0.05
50% /Int Spd	67.95	1902.00	0.32	0.44	5.71	788.78	0.07
Low idle	8.19	634.50	1.26	3.30	6.12	401.53	0.10
C1 E_{mf}			0.37	0.90	5.74	884.05	0.12

Extra Data Points

Int load/IS	93.43	1502.00	0.11	0.38	6.58	641.82	0.03

Ottawa Yard Truck Eng Hr/Odometer 8195.00
Cummins 2001 C8.3L
using CARB Diesel

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	106.92	2203.50	0.22	1.37	8.38	981.54	0.37
75%/Rtd Spd	81.44	2202.50	0.47	0.99	7.98	1011.25	0.29
50%/Rtd Spd	54.46	2201.00	0.88	1.24	8.14	1172.24	0.37
10%/Rtd Spd	10.99	2201.00	3.10	5.96	18.96	3764.49	2.13
100%/Int Spd	104.92	1899.00	0.24	1.15	8.55	904.76	0.30
75%/Int Spd	77.44	1902.00	0.24	0.67	8.02	912.57	0.22
50% /Int Spd	52.46	1900.00	0.71	0.95	7.54	995.84	0.28
Low idle	10.69	592.00	0.68	1.15	5.55	304.88	0.04
C1 E_{mf}			0.46	1.19	8.30	1023.47	0.34

Extra Data Points

Int load/IS	63.95	1602.00	0.31	0.52	8.46	866.40	0.23
<100/RS-match Emulsifed Diesel	89.43	2198.00	0.61	1.15	8.35	1035.70	0.33
<100/IS-match Emulsifed Diesel	97.43	1899.50	0.28	1.04	8.31	916.53	0.29

Ottawa Yard Truck Eng Hr/Odometer 9999.00
Cummins 2001 C8.3L
using Emulsified Diesel

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	90.43	2195.00	0.52	0.72	6.11	991.86	0.15
75%/Rtd Spd	81.44	2200.50	0.33	0.75	6.22	1001.94	0.15
50%/Rtd Spd	53.46	2201.50	0.74	1.08	6.71	1170.14	0.20
10%/Rtd Spd	11.49	2202.00	2.26	6.60	15.96	3468.46	0.78
100%/Int Spd	98.92	1902.00	0.41	0.64	6.63	905.22	0.13
75%/Int Spd	77.44	1899.00	0.27	0.60	6.15	909.89	0.13
50% /Int Spd	52.46	1899.50	0.49	0.84	6.17	989.54	0.13
Low idle	9.04	625.50	1.45	3.84	6.05	404.30	0.04
C1 E_{mf}			0.51	0.94	6.50	1027.02	0.16

Extra Data Points

Int load/IS	63.95	1600.00	0.30	0.60	6.33	875.45	0.15

Capacity Yard Truck | Eng Hr/Odometer | 451.00 | Not all modes were done due to transmission shifting
1997 Cummins C8.3L
using CARB diesel

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	124.41	2403.50	0.15	0.31	2.90	1028.80	0.20
75%/Rtd Spd	92.93	2398.50	0.24	0.35	3.03	1093.36	0.17
50%/Rtd Spd	61.95	2398.00	0.33	0.66	3.38	1257.92	0.26
10%/Rtd Spd	11.99	2403.50	2.15	6.84	10.62	4033.58	1.04
100%/Int Spd	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
75%/Int Spd	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
50% /Int Spd	41.47	1800.50	0.41	0.34	4.91	1181.09	0.15
Low idle	12.44	701.00	0.35	0.28	3.83	472.27	0.05
C1 E_{mf} Not Available-missing Modes							

Capacity Yard Truck | Eng Hr/Odometer | 453.00 | Not all modes were done due to transmission shifting
1997 Cummins C8.3L
using Emulsified diesel

Test Mode		453.00	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	m CO	m NOx	CO2	PM
100%/Rtd Spd	101.42	2402.00	0.19	0.35	2.55	1094.28	0.13
75%/Rtd Spd	92.93	2398.00	0.21	0.43	2.59	1109.79	0.13
50%/Rtd Spd	61.95	2404.50	0.36	1.26	2.95	1294.14	0.21
10%/Rtd Spd	11.99	2398.00	3.53	34.47	10.04	4000.38	0.78
100%/Int Spd	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
75%/Int Spd	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
50% /Int Spd	40.96	993.50	0.48	0.97	4.05	1208.95	0.11
Low idle	10.14	700.00	0.69	3.24	3.63	594.27	0.03
C1 E_{mf} Not Available-missing Modes							

Capacity Yard Truck | Eng Hr/Odometer | Not Available
2004 Cummins QSB 5.9L
using LS Diesel

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	122.50	2507.00	0.12	0.41	5.49	827.83	0.14
75%/Rtd Spd	90.50	2492.00	0.14	0.56	4.90	944.40	0.16
50%/Rtd Spd	61.50	2501.50	0.18	0.87	4.89	1117.43	0.18
10%/Rtd Spd	12.00	2500.50	1.30	4.31	18.11	3344.00	0.42
100%/Int Spd	134.00	2202.50	0.08	0.36	5.76	730.10	0.12
75%/Int Spd	102.00	2202.00	0.14	0.39	5.11	765.07	0.09
50% /Int Spd	68.50	2200.00	0.17	0.58	4.83	878.16	0.09
Low idle	12.25	750.00	0.27	1.29	4.17	359.15	0.02
C1 E_{mf}			0.15	0.58	5.41	892.18	0.14
Extra Data Points							
Int load/IS	42.50	1500.00	0.23	0.32	7.27	805.84	0.04

Ottawa Yard Truck | Eng Hr/Odometer | Not Available
2004 Cummins ISB 5.9L
using LS Diesel

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	164.50	2298.00	0.03	0.56	2.11	785.53	0.11
75%/Rtd Spd	123.50	2301.50	0.04	0.43	2.27	832.49	0.07
50%/Rtd Spd	82.50	2304.50	0.05	0.56	2.65	958.43	0.09
10%/Rtd Spd	16.50	2308.50	0.47	3.54	6.65	2815.44	0.32
100%/Int Spd	133.50	2006.50	0.04	0.51	2.06	787.58	0.09
75%/Int Spd	101.00	2003.50	0.04	0.46	2.14	810.43	0.10
50% /Int Spd	67.00	2001.50	0.06	0.62	2.46	931.81	0.12
Low idle	16.45	700.50	0.05	0.32	4.55	269.70	0.01
C1 E_{mf}			0.05	0.57	2.39	856.06	0.10

Extra Data Points

Int load/IS	79.50	1501.00	0.04	0.40	2.62	764.06	0.06

Kalmar Yard Truck Eng Hr/Odometer 1199
Cummins 2004 5.9L LPG

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	133.90	2600.00	0.20	0.01	6.18	814.65	0.016
75%/Rtd Spd	99.42	2598.00	0.06	0.01	2.41	862.27	0.008
50%/Rtd Spd	65.95	2601.00	0.20	0.01	2.11	1069.87	0.005
10%/Rtd Spd	12.98	2601.50	0.31	0.04	9.14	3436.44	0.009
100%/Int Spd	116.41	1798.00	0.16	0.01	3.20	675.49	0.002
75%/Int Spd	85.93	1814.50	0.06	0.03	1.92	703.78	0.001
50% /Int Spd	54.95	1808.00	0.30	0.01	2.09	861.34	0.001
Low idle	13.39	750.50	0.09	2.04	0.35	535.58	0.003
C1 E_{mf}			0.14	0.07	3.49	863.85	0.007

Kalmar Yard Truck Eng Hr/Odometer 482.00
Cummins 2005 8.3L LNG

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (wHp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	182.19	2378.51	2.07	0.13	5.66	605.91	0.02
75%/Rtd Spd	132.57	2388.24	2.93	0.08	3.95	664.68	0.01
50%/Rtd Spd	88.93	2422.42	4.16	0.05	2.89	794.02	0.01
10%/Rtd Spd	17.99	2401.69	14.85	0.06	6.92	2303.54	0.02
100%/Int Spd	184.53	2106.47	2.11	0.10	5.24	552.81	0.01
75%/Int Spd	134.56	2107.08	2.73	0.05	3.03	597.83	0.00
50% /Int Spd	89.93	2103.98	3.81	0.03	1.93	693.81	0.00
Low idle	18.22	699.17	1.78	0.02	0.30	303.32	0.00
C1 E_{mf}			2.94	0.09	4.15	658.720	0.011

Capacity Yard Truck Eng Hr/Odometer 766.00
Caterpillar 2005 C7 7.2L with DOC using CARB diesel

Test Mode			g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr	g/whp-hr
Percent Load/Speed	Load (whp)	RPM	THC	CO	NOx	CO2	PM
100%/Rtd Spd	139.39	2446.99	0.06	0.36	2.63	831.81	0.09
75%/Rtd Spd	103.42	2472.79	0.11	0.45	2.81	922.46	0.04
50%/Rtd Spd	69.45	2485.03	0.21	0.69	2.91	1138.68	0.04
10%/Rtd Spd	13.99	2486.63	1.21	0.54	8.74	3841.70	0.60
100%/Int Spd	146.39	2272.51	0.04	0.26	2.84	781.31	0.08
75%/Int Spd	113.41	2281.37	0.06	0.31	2.48	852.48	0.08
50% /Int Spd	75.44	2274.94	0.14	0.43	2.98	1013.69	0.03
Low idle	13.94	745.42	0.23	2.88	3.47	351.79	0.02
C1 E_{mf}			0.12	0.47	2.87	935.257	0.074

Appendix 2

Chemical Analysis and Physical Properties for Low-sulfur Diesel Listed as CARB Certified Ultra Low Sulfur (ULSD)

Petroleum Diesel Chemical/Physical Tests

Property	ASTM Test Method	Limits	Units	CARB Certified ULSD	JP-8
API Gravity	D287			38.5	39.3
Specific Gravity				0.832	0.828
Aromatics	D1319		% Vol.	19.3	16.0
Btu Content – Net Heating Value	D240		Btu/gal	128,413	127,530
Rams Carbon Residue on 10% btms.	D 524	0.350 max.	% Mass	0.1	0.05
Cetane Number	D613	40 min.		54.4	36.3
Cetane Index	D976			51.92	36.4
Cloud Point	D 2500	Report	°C	-5	<-21
Copper Strip Corrosion	D 130	No. 3* max.		1a	1a
Distillation at 90%	D 86	338 max.	°C	328	242
Flash Point	D 93	130.0 min.	°C	159.8	130
Kinematic Viscosity, 40°C	D 445	1.9 – 6.0	mm^2/s	2.602	1.484
Ash	D 482	0.010 max.	% Mass	<0.001	<0.001
Sulfur	D 5453	0.05 max.	% Mass	0.0002	0.0461
Water and Sediment	D 2709	0.050 max.	% Volume	0	0

Note: ASTM D975, the specification for petroleum diesel fuels, requires the fuel to meet the properties identified in ***Bold and Italic.*** * Comparison to a color chart for corrosion.

Appendix 3

LNG Yard Truck Fuel Analysis: LNG (Vaporized) Samples Analyzed for Composition by Gas Chromatography

Sample 1 LNG Run 3	Area Counts	Area%
Methane	11867400.00	92.36
Ethane	658799.00	5.13
Ethylene	3757.00	0.03
Propane	146748.00	1.14
Propene	28570.80	0.22
Butane	24306.10	0.19
2M-butane	9708.00	0.08
Pentane	5505.00	0.04
c5	537.00	0.00
c5	2351.00	0.02
Hexane	913.00	0.01
Benzene	25929.80	0.20
Toluene	73970.30	0.58
	12848495.00	

Sample 2 LNG Run 5	Area Counts	Area%
Methane	28139600.00	93.21
Ethane	1175000.00	3.89
Ethylene	0.00	0.00
Propane	387866.00	1.28
Propene	85554.00	0.28
Butane	78267.20	0.26
2M-butane	37779.20	0.13
Pentane	23242.40	0.08
c5	1501.00	0.00
c5	2351.00	0.01
Cyclohexane	2816.00	0.01
c6	2621.00	0.01
c6	1362.00	0.00
c6	11908.10	0.04
Hexane	4403.00	0.01
Benzene	1400.00	0.00
Toluene	232558.00	0.77
	30188228.90	

Sample Name M4 test 1 LNG Run 5 Mode 4

Sample Info LNG sample 2000:1
Acq. Method 04GC2CO1.M
Injection Date 06-Jun-06, 10:01:15

RetTime	Area counts	ppmC	AreaPercent	
1.2667	14829182.0000	549.8108	99.1361	00074-82-8 Methane
2.3836	97192.0625	3.7708	0.6497	00074-84-0 Ethane
3.8542	0.0000	0.0000	0.0000	00074-85-1 Ethene
4.9566	19850.5137	0.7701	0.1327	00074-98-6 Propane
6.7483	28.1901	0.0011	0.0002	00115-07-1 Propene
7.0090	4301.1270	0.1733	0.0288	Unknown
7.2190	4000.1375	0.1552	0.0267	00106-97-8 Butane
7.5010	0.0000	0.0000	0.0000	00463-49-0 Propadiene
7.6281	0.0000	0.0000	0.0000	00074-86-2 Ethyne
8.5185	0.0000	0.0000	0.0000	00106-98-9 1-Butene
8.6532	0.0000	0.0000	0.0000	00624-64-6 t-2-Butene
8.8710	367.4697	0.0143	0.0025	00590-18-1 c-2-Butene
8.9657	0.0000	0.0000	0.0000	00115-11-7 2M-Propene
9.1661	217.5008	0.0084	0.0015	00463-82-1 2*2-DM-Propane
9.5317	63.8396	0.0025	0.0004	00078-78-4 2M-Butane
9.7865	1960.0869	0.0760	0.0131	00074-99-7 Propyne
10.1906	1240.2323	0.0481	0.0083	00109-66-0 Pentane
11.0119	0.0000	0.0000	0.0000	00106-99-0 1*3-Butadiene

Sample M1 test 2 LNG Run 5 Mode 1
Sample Info LNG sample 2750:1
Method 04GC2CO1.M
Date 06-Jun-06, 10:36:43

RetTime	Area	ppmC	AreaPercent	
1.2684	9406762.0000	348.7677	97.9415	00074-82-8 Methane
2.3867	159092.5000	6.1724	1.6564	00074-84-0 Ethane
3.8542	0.0000	0.0000	0.0000	00074-85-1 Ethene
4.9702	26938.5313	1.0451	0.2805	00074-98-6 Propane
6.6100	0.0000	0.0000	0.0000	00115-07-1 Propene
7.0262	4771.1484	0.1851	0.0497	Unknown
7.2362	4164.6948	0.1616	0.0434	00106-97-8 Butane
7.5010	0.0000	0.0000	0.0000	00463-49-0 Propadiene
7.6281	0.0000	0.0000	0.0000	00074-86-2 Ethyne
8.5185	0.0000	0.0000	0.0000	00106-98-9 1-Butene
8.6532	0.0000	0.0000	0.0000	00624-64-6 t-2-Butene
8.9183	163.6642	0.0063	0.0017	00590-18-1 c-2-Butene
8.9657	0.0000	0.0000	0.0000	00115-11-7 2M-Propene
9.1667	43.6645	0.0017	0.0005	00463-82-1 2*2-DM-Propane
9.5628	34.5809	0.0013	0.0004	00078-78-4 2M-Butane
9.8159	1595.8024	0.0619	0.0166	00074-99-7 Propyne
10.2221	905.6349	0.0351	0.0094	00109-66-0 Pentane
11.0119	0.0000	0.0000	0.0000	00106-99-0 1*3-Butadiene

Appendix 4

Westport Innovations, Inc. Summary of LNG Yard Truck Fuel System Analysis and Modifications

Westport (independently from Cummins Westport, Inc.) reviewed the installation of the fuel system on the vehicles at YTI. The LNG fuel system included everything from the LNG tank to the inlet of the engine filter. This system is the responsibility of the vehicle OEM and LNG tank manufacturer and is installed independently from the engine. The same fuel system configuration was present on vehicle H181 during both the March and May testing at UC riverside. The range of acceptable pressure to the engine is 70 psig to 150 psig. Please note that the low fuel warning only occurs at 60 psi. Thus, you may see no fuel warnings yet still be operating beyond the designed pressure range of 70 psig to 150 psig.

There were three main issues with the fuel system that restricted available pressure (flow) to the engine. The first was the setting on the over pressure regulator. This regulator is used to assure the pressure to the engine does not exceed the 150 psi maximum inlet pressure rating of the C+ gas. When testing this regulator, it was noted that the locking feature was missing from the regulator, and the setting on the regulator restricted upstream pressure to 65 psi. Under low load conditions and during transient operation, it is certainly possible for the pressure to exceed 65 psi. However, during high load and high flow situations, the pressure would be restricted to near 65 psi.

The second issue was the setting of the economizer (back pressure regulator) on the tank. The purpose of this regulator is to manage tank pressure. It will reduce tank pressure by allowing gas flow to the engine until the set-point is reached. After the set-point is reached, the gas flow stops, and 100 percent of the fuel flow to the engine is drawn from liquid in the tank. The setting on this regulator was 85 psig. Thus, even when fueled at high pressure, the pressure in the tank and hence the pressure available to the engine, would reduce rapidly. Tank pressure of 85 psig only allows for 15 psi of pressure drop between tank and engine. Even with a properly configured fuel system, this is not adequate to prevent low fuel pressure conditions.

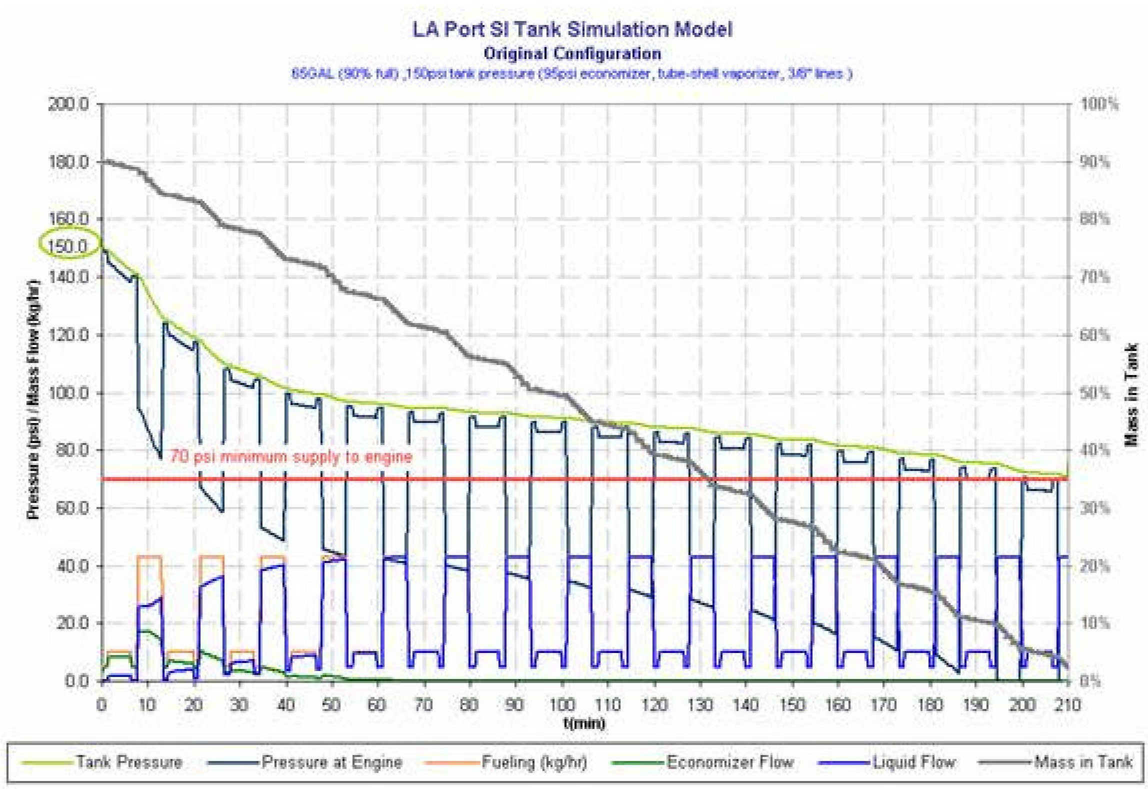
Lastly, the overall configuration of plumbing on the vehicle created excessive pressure drop from tank to engine. The majority of tubing was 3/8” OD, and excessive lengths, bends, and fittings were used in this installation. The use of small diameter tubing and a convoluted path from tank to engine produced excessive pressure drop and hence, low pressure at the engine during high fuel flow conditions.

All of these conditions have lead to a vehicle that did not allow sufficient pressure available to the engine during normal operating conditions.

The following analytical model, using the original configuration of the fuel system on H181, shows the influence of these issues. The analysis assumes:

- the tank on H181 was filled with saturated LNG at 150 psi;
- the economizer is set at 95 psi. The actual setting was found later to be lower (85 psi) which would create lower tank and engine delivery pressures on the vehicle than those seen in this model; and
- a typical vehicle cycle at the port involved the following fueling requirements:
  - ❖ Idle (loading): 5 kg/hr 1 minute
  - ❖ Run loaded: 45 kg/hr 5 minutes
  - ❖ Idle (unloading): 5 kg/hr 1 minute
  - ❖ Run empty: 10 kg/hr 5 minutes

Figure 1. Fuel System analysis for YTI port vehicle H181



The first observation is the rapid reduction in tank pressure followed by a slower decrease as indicated by the light green line "Tank Pressure". You can see the tank starts at 150psi. The tank pressure drops quickly as fuel consumption begins. During this period of rapid pressure decrease, you can see that the economizer is open, allowing gas to be drawn from the tank. This flow is labeled as "Economizer Flow". Once the Economizer closes, at ~60 minutes into the trial, the rapid decrease in tank pressure is replace by a more gradual decrease. Although the fuel consumption rate is consistent throughout the test, the rate of tank pressure decrease is not. The tank drops 55psi in the first 60 minutes of the simulation and then drops the next 10 psi in the following 150 minutes. This rate change is due to two fundamental differences between drawing gas and drawing liquid out of the tank. The first is that the energy displaced by vapor leaving the tank is equivalent to approximately four times the energy displaced by the liquid on a mass basis. The second is difference in specific gravity between gas and liquid.

As can be seen in the simulation shown in Figure 1, the "Pressure at Engine" drops below the 70 psi minimum pressure (shown in red) during periods of high fuel consumption almost immediately. As the tank is drained, the occurrence of low fuel faults increases. It is predicted in this simulation that the pressures to the engine are low enough to stop the engine from operating even when the tank has a significant amount of fuel remaining.

It is clear from this analysis, observations during testing, and interviews of the drivers that the fuel pressure to the engine was frequently outside of the specified range for the CWI C+ Gas engine. This occurred both during regular operation and during the emissions testing that occurred at UC Riverside.