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Emissions of Transport Refrigeration Units with CARB Diesel, Gas-to-Liquid Diesel, and Emissions Control Devices

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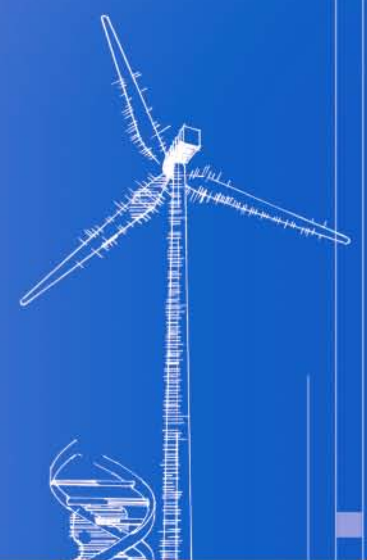

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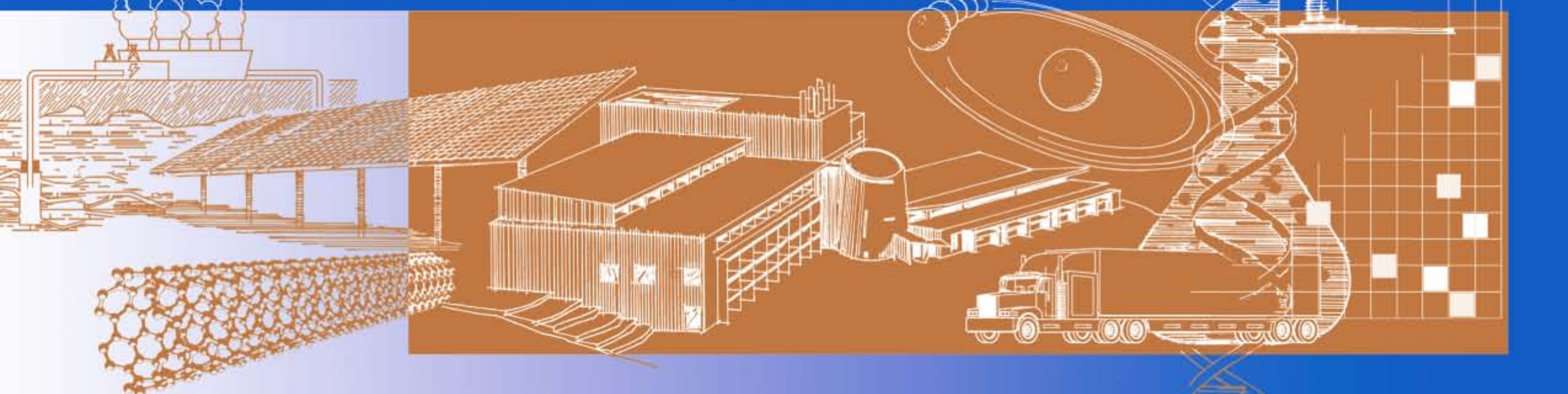

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ABSTRACT

A novel in situ method was performed for measuring emissions and fuel consumption of transport refrigeration units (TRUs). The test matrix included two fuels, two exhaust configurations, and two TRU engine operating speeds. The test fuels were California ultra low sulfur diesel and gas-to-liquid (GTL) diesel. The exhaust configurations were a stock original equipment manufacturer (OEM) muffler and a Thermo King pDPF diesel particulate filter. The two TRU engine operating speeds were high and low, as controlled by the TRU user interface.

Test results indicate that GTL diesel fuel reduces all regulated emissions at high and low engine operating speeds. Separately, the application of a Thermo King pDPF reduced regulated emissions, in some cases almost entirely. Finally, the application of both GTL diesel and a Thermo King pDPF reduced regulated emissions at high engine operating speed, but with an increase in oxides of nitrogen (NO_x) at low engine speed.

INTRODUCTION

Transport refrigeration units (TRUs) are refrigeration systems designed to refrigerate or heat perishable products that are transported in various containers, including semi-trailers (Figure 1), box trucks, vans, shipping containers, and rail cars.

Figure 1. TRU Mounted on Trailer Nose

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TRUs are powered predominantly by diesel internal combustion engines. While TRU engines are relatively small, ranging from 9 to 36 horsepower (hp), significant numbers of vehicles with these engines congregate at distribution centers, truck stops, and other facilities, posing significant health risks to those who live and work nearby.

The California Air Resources Board (CARB) estimates that there are 40,200 TRUs operating in California at any given time, with an annual diesel consumption of more than 20 million gallons. CARB also estimates that TRU particulate matter (PM) and nitrogen oxides (NO_x) emissions are 2 and 20 tons per day (tpd), respectively. The PM emission contribution from TRUs is estimated at 2.6% of total diesel PM emissions. PM emissions are projected to increase to about 2.5 tpd in 2010 and to more than 3 tpd by 2020.

The nature of the TRU emissions inventory, as well as CARB's identification of diesel PM as a toxic air contaminant, led to CARB's adoption of an Airborne Toxic Control Measure (ATCM) for TRUs and TRU generator sets on February 26, 2004.[1]

The ATCM includes a phased compliance schedule based upon TRU model year; older units require compliance sooner.[2] The three principal methods of compliance include the following:

1. Replacing the existing TRU engine with a certified engine meeting applicable nonroad/off-road emissions standards
2. Equipping the engine with a required level of Verified Diesel Emission Control Strategy (VDECS)
3. Operating a TRU or TRU gen set meeting one of several alternative technology options.

Alternative technology options include fuel cells, electric standby, cryogenic temperature control systems, alternative fuels with a VDECS, and alternative diesel fuels that have been verified as a VDECS. Examples of alternative diesel fuels include biodiesel and gas-to-liquid (GTL) synthetic diesel. In on-road engines, GTL diesel fuel has been shown to reduce PM emissions without accompanying increases in other regulated emissions.[3,4]

There have been few studies on TRU emissions and performance with a VDECS or alternative technologies.[5,6,7] Nevertheless, many parties are interested in the operability of and emissions from TRUs using various combinations of VDECS and alternative technologies:

- TRU end users (fleets) in need of operability data
- Regulators in need of emissions data
- TRU original equipment manufacturers (OEMs) in need of emissions data for compliance and operability data for warranties.

OBJECTIVES

This paper reports on one component of a larger collaborative project. The primary objective of the activities reported here was to measure the fuel consumption and emissions of a TRU fueled with GTL diesel or CARB ultra low sulfur diesel and equipped with either a Level 2 VDECS or the stock OEM muffler. Secondary objectives were to evaluate fuel consumption impacts due to backpressure with the Thermo King diesel particulate filter, known as pDPF, and to evaluate pDPF performance on equipment outside the terms of its CARB verification.

APPROACH

INTRODUCTION – This project was conducted under a cooperative research and development agreement between the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory (NREL) and the South Coast Air Quality Management District (SCAQMD). Funding was supplied by SCAQMD and the Advanced Petroleum-Based Fuels Task sponsored by DOE's Vehicle Technologies Program. Additional project partners and their roles are listed in Table 1.

Table 1. Project Partners and Roles

Project Partner	Project Role
NREL	Co-funder, project lead
SCAQMD	Co-funder
CARB	Emissions testing
Thermo King	VDECS, engine teardown
SasolChevron	GTL diesel test fuel for in-use evaluation and emissions testing

SYSTEM DESCRIPTION – The subject TRU is a model year 2004 Thermo King brand SB-200 30 model, mounted to a 48-foot trailer. The engine is a Yanmar 2.2 liter, four-cylinder in-line diesel. The engine utilizes mechanically direct injection and is naturally aspirated.

The engine shaft power is applied through a direct drive coupling to a refrigeration compressor off the flywheel. On the front of the engine, a belt system drives the alternator and an engine compartment cooling fan. The TRU operates at two engine speeds (1450 and 2200 rpm) which are mechanically governed by the fuel injection pump. A general TRU schematic is shown in Figure 2. The enclosure skins, electrical controls, belts, and blower are not shown.

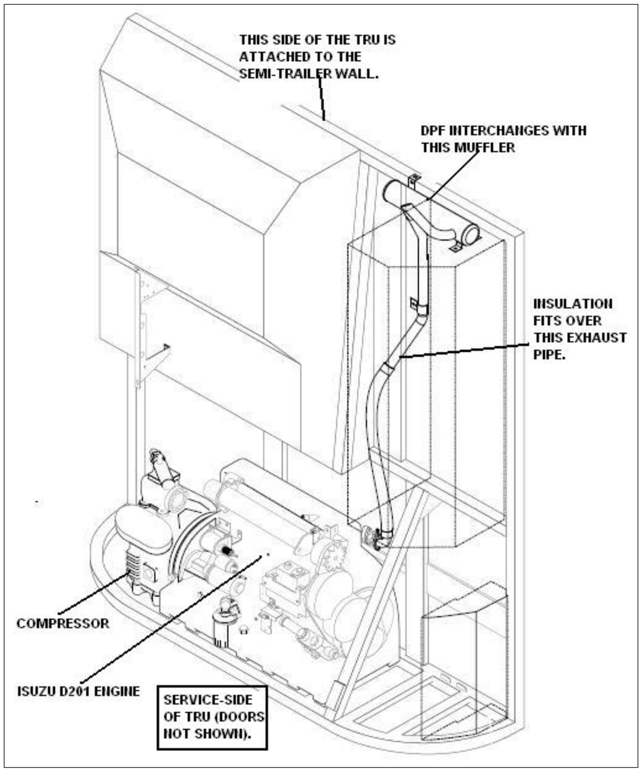

Figure 2. TRU Power Pack Schematic

EXHAUST AFTERTREATMENT – The Level 2 VDECS used in this testing is a Thermo King pDPF. The Thermo King pDPF was verified by CARB as a Level 2 device (achieves a greater than or equal to 50% reduction in diesel PM). Additionally, the Thermo King pDPF was found not to increase NO_2 emissions more than 20% compared with the baseline, indicating compliance with the 2009 NO_2 emissions limit (13 CCR section 2706(a)) and thus obtaining designation as a "Plus" system per Section 2702(f).[8] The CARB verification cited is for engine model years 2002 and older; the TRU unit tested is a model year 2004.

The principle of operation of the Thermo King pDPF is a flow-through design, utilizing knitted wire elements that provide a tortuous path. Passive regeneration of the soot is triggered by a proprietary catalyst on the mesh elements. The pDPF is designed to regenerate when the exhaust temperature is in the 230ºC to 450ºC range. A simple control system increases engine speed when a backpressure limit is reached to increase exhaust temperature and initiate soot regeneration. The wire mesh element is shown in Figure 3.

Figure 3. Thermo King pDPF Wire Mesh Element

TEST FUELS – Test fuels were CARB ultra low sulfur diesel and GTL diesel. CARB diesel was supplied by a local distributor of Chevron Products Company. This fuel was not analyzed but was presumed to meet the fuel specification for CARB diesel. CARB diesel is characterized by a maximum 10% by volume aromatics and minimum cetane number of 48. SasolChevron supplied GTL diesel for emissions testing. This fuel was characterized by zero aromatic content and a cetane number of 81. The appendix presents both the GTL diesel production lot analytical results and CARB diesel fuel specification for comparison.

EMISSIONS TESTING – TRU emissions and fuel consumption measurements were conducted at the CARB Stockton laboratory (SL). The CARB SL is a heavy-duty vehicle emissions laboratory configured to test heavy-duty diesel-powered vehicles on a twin roll, 1,100 hp chassis dynamometer. In addition to wheeled vehicle tests, the SL can also perform emissions measurements on other utility equipment, such as TRUs and transportable air compressors.

All gaseous emissions were measured in the raw exhaust using conventional laboratory-grade analyzers manufactured by California Analytical Instruments. These included a heated flame ionization detector (HFID) for total hydrocarbon (THC) measurements, two heated chemiluminescence analyzers for total NO_x and NO measurements, an infrared detector for CO and CO_2 measurements, and a paramagnetic analyzer for O_2 measurements. Air flow through the engine was measured using a calibrated air turbine installed on the engine air intake.

PM was sampled by drawing a separate exhaust stream through a Sierra BG-2 partial flow sampling system (PFSS). The sampling stream temperature was held below 52ºC. PM samples were collected using a variety of dilution ratios and sampling times (depending on the test mode) on primary and secondary 90 mm T60A20 filter media. The filters were preconditioned in a temperature and humidity-controlled weighing room before and after sample collection and then measured gravimetrically on a Mettler Toledo UMX 2 microbalance.

Fuel consumption was measured using a gravimetric fuel measurement system integrated with a data acquisition system; both are manufactured by Superflow, Inc. A 22-gallon fuel can suspended by a torque cell provides real-time fuel consumption data. Both fuel supply and return lines are routed to the fuel can. Return fuel is passed through a water-to-fuel heat exchanger prior to being returned to the can. When in operation, the test equipment's fuel tank is bypassed completely, operating only on fuel supplied by the can.

Calibration is obtained through the use of certified weights placed on a purpose-designed stand. American Petroleum Institute (API) specific gravity is calculated by filling and emptying the can. The known volume, measured weight, and measured fuel temperature are used by the Superflow data acquisition system to calculate the API value, which is displayed as a data channel. Additional verification of the API value is obtained with the use of a temperature-corrected hydrometer.

The TRU was tested in situ as a complete operational unit. Unlike a certification test, the engine was not removed for testing on an engine dynamometer. The unaltered TRU was controlled using the Thermo King user interface, which controls the load placed on the diesel engine by varying the cooling command to the refrigerant compressor. Steady-state conditions were achieved by cooling the trailer box to a low temperature and then adjusting the cooling set point upward, resulting in a stabilized and repeatable engine load. This stabilized mode was verified by monitoring several parameters as a surrogate for direct load measurement. These stabilized load verification parameters included the refrigerant compressor high and low side pressures and fuel consumption. Continuous gaseous and engine operating conditions were recorded, and multiple PM filter samples were taken during the stabilized operation.

TEST MATRIX – Testing involved two fuels, two engine operating speeds, and two exhaust configurations. A total of eight combinations were tested with duplicate test runs (Table 2).

Table 2. TRU Test Matrix

Test Run	Fuel	Engine Speed	Exhaust
1	CARB diesel	Low	OEM muffler
2	CARB diesel	High	OEM muffler
3	CARB diesel	Low	pDPF
4	CARB diesel	High	pDPF
5	GTL Diesel	Low	OEM muffler
6	GTL Diesel	High	OEM muffler
7	GTL Diesel	Low	pDPF
8	GTL Diesel	High	pDPF

The high and low TRU engine speeds are nominally 2200 and 1450 rpm, respectively. Between each fuel change, the fuel system was flushed clean and the engine was operated on the new test fuel for approximately two hours.

RESULTS

Steady-state conditions were achieved using the method described previously and confirmed by evaluating several key parameters. Engine speed (rpm), fuel consumption (gph), compressor outlet pressure (psi) and exhaust manifold temperature (ºF) were evaluated as indicators of steady-state operation. The figures below present one test that is representative of steady-state conditions achieved for all test runs. Engine speed and fuel consumption (Figure 4) and exhaust temperature and compressor outlet pressure (Figure 5) remain constant during the test procedure, indicating steady-state conditions.

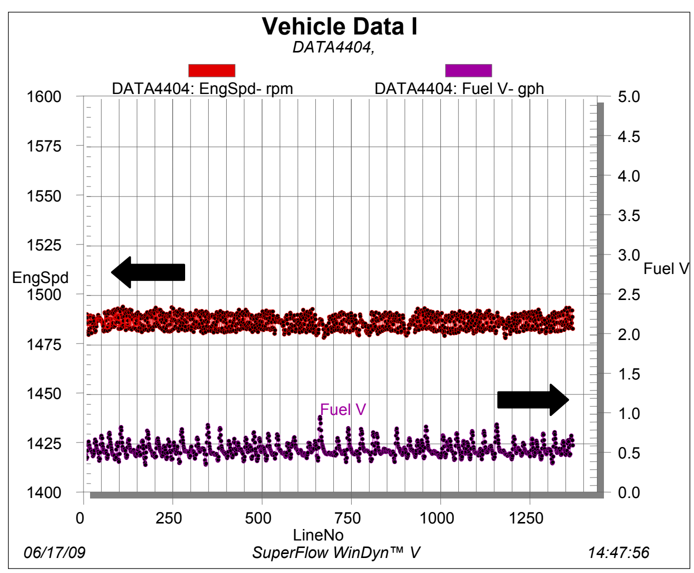

Figure 4. Steady-State Test Conditions for Engine Speed and Fuel Consumption

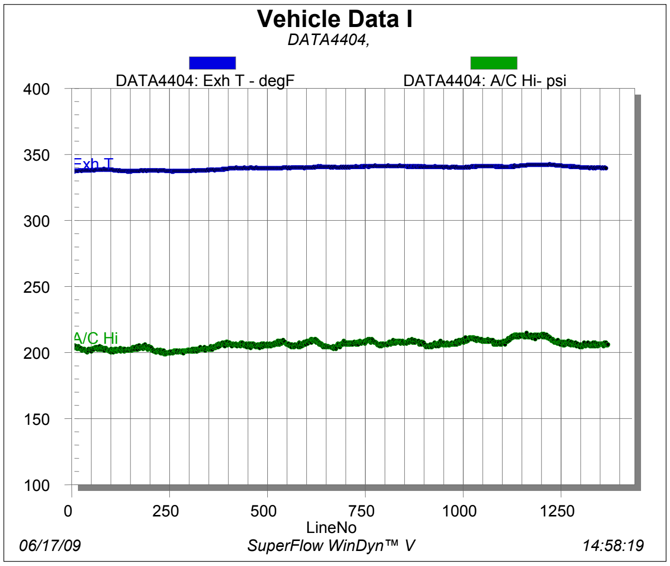

Figure 5. Steady-State Test Conditions for the Compressor High-Pressure Outlet and Exhaust Temperature

Gaseous emissions results also indicate that steady-state conditions were achieved using this test methodology (Figure 6). Downward spikes at consistent intervals are representative of emissions bench air injections and visually separate test runs.

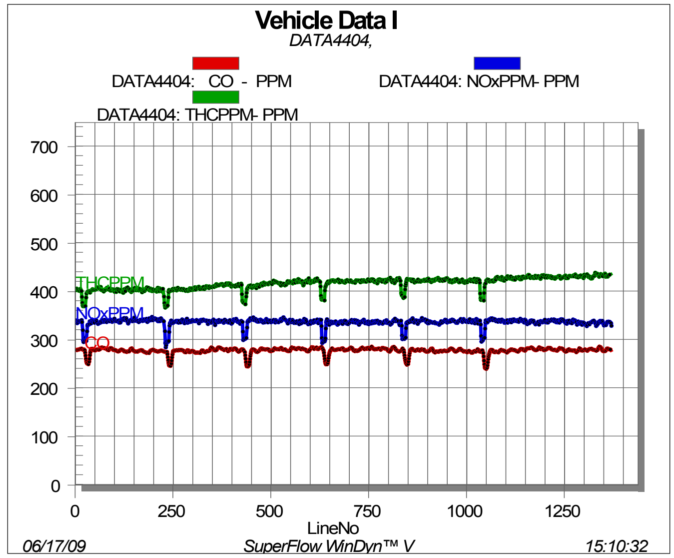

Figure 6. Steady-State Gaseous Emissions

Two runs per test configuration were conducted, and the results were averaged (Table 3). Two NO_x analyzers were used to measure total NO_x and NO. The NO_2 and the ratio of NO/NO_2 were calculated and are also presented in Table 3. The second NO_x analyzer failed during test runs of GTL diesel fuel with the pDPF; NO results are designated as not measured (NM).

Table 3. TRU Emissions Results

Fuel	Engine Speed	Exhaust	NOx (g/hr)	NO (g/hr)	NO_2 (g/hr)	NO/ NO_2	CO (g/hr)	CO_2 (g/hr)	THC (g/hr)	PM (g/hr)	Fuel Consumption (gal/hr)
CARB	High	Muffler	123.34	104.37	18.96	5.50	61.80	17,975	37.28	17.60	1.31
GTL	High	Muffler	107.49	90.11	17.38	5.18	49.94	17,834	29.21	12.89	1.35
CARB	High	pDPF	123.95	92.08	31.87	2.89	0.73	19,715	1.56	13.98	1.33
GTL	High	pDPF	108.97	NM	NA	NA	0.21	18,599	1.08	9.13	1.28
CARB	Low	Muffler	53.89	41.67	12.21	3.41	30.77	6,222	24.92	6.49	0.56
GTL	Low	Muffler	45.47	34.05	11.42	2.98	25.40	5,796	14.22	3.87	0.53
CARB	Low	pDPF	52.38	45.58	6.80	6.70	10.40	6,423	17.50	2.77	0.51
GTL	Low	pDPF	59.88	NM	NA	NA	0.69	5,532	5.94	1.81	0.48

Emissions and fuel consumption duplicate test run results are compared across the test matrix in Figures 7–12.

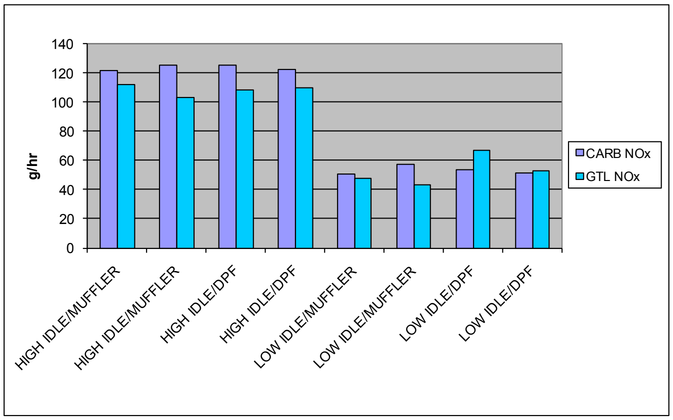

Figure 7. NO_x Emissions

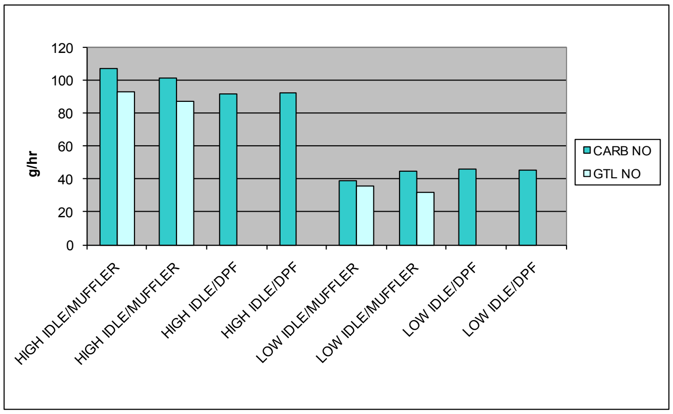

Figure 8. NO Emissions

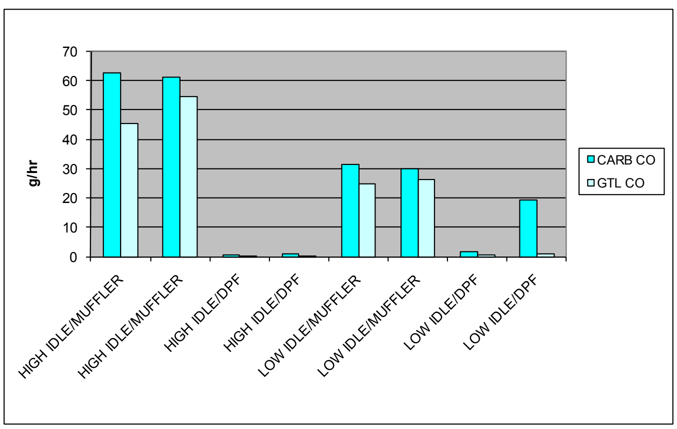

Figure 9. CO Emissions

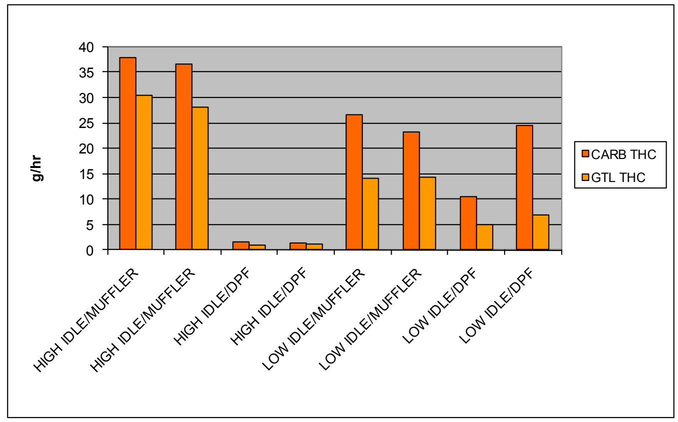

Figure 10. THC Emissions

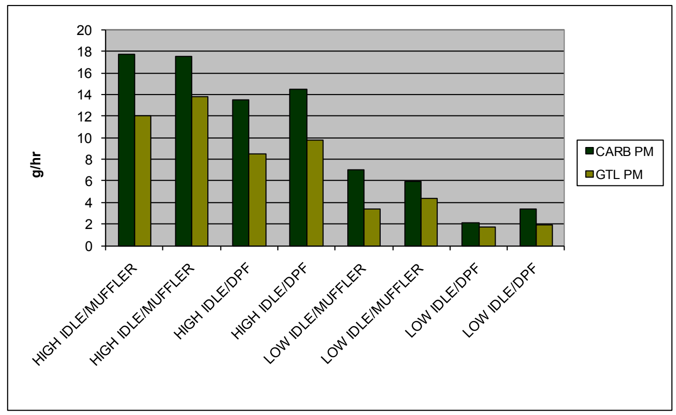

Figure 11. PM Emissions

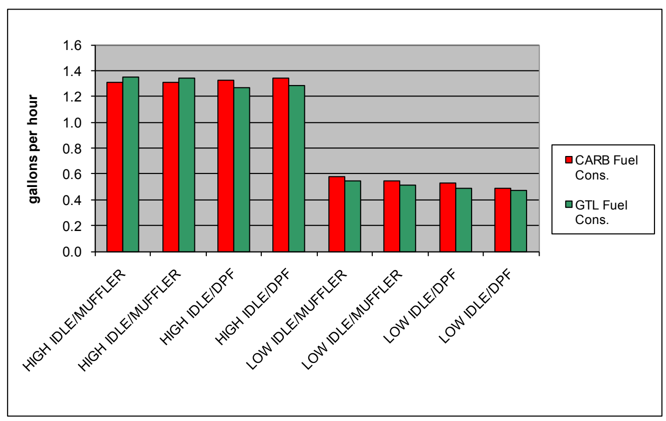

Figure 12. Fuel Consumption

Compared with the baseline condition of CARB diesel and a stock muffler, significant reductions of gaseous emissions and PM are possible when utilizing GTL diesel, a Thermo King pDPF, or combining the two approaches. Table 4 presents the percentage decreases measured in each case, and additional discussion follows.

Table 4. Emissions Reductions with GTL Diesel and/or Thermo King pDPF

Engine Speed	NO_x	NO	NO_2	CO	CO_2	THC	PM	Fuel Consumption
Reductions with GTL diesel as replacement for CARB diesel								
High	-12.8%	-13.7%	-8.3%	-19.2%	-0.8%	-21.7%	-26.8%	+2.9%
Low	-15.6%	-18.3%	-6.5%	-17.4%	-6.8%	-42.9%	-40.4%	-6.4%
Reductions with pDPF as replacement for muffler								
High	+0.5%	-11.8%	+68.1%	-98.8%	+9.7%	-95.8%	-20.6%	+2.0%
Low	-2.8%	+9.4%	-44.3%	-66.2%	+3.2%	-29.8%	-57.3%	-9.3%
Reductions with both GTL diesel and pDPF								
High	-11.6%	NM	NA	-99.7%	+3.5%	-97.1%	-48.1%	-2.2%
Low	+11.1%	NM	NA	-97.8%	-11.1%	-76.2%	-72.1%	-14.4%

Note: Figures preceded by a minus sign (e.g., -12.8%) denote a reduction from the baseline, while those preceded by a plus sign (e.g., +2.9%) denote an increase.

Reductions in PM are the primary focus of the CARB ATCM and ultimately of this project. Replacing CARB diesel with GTL diesel yielded PM reductions of 27%–40%, depending on engine speed. Replacing the OEM muffler with a Thermo King pDPF resulted in PM reductions of 21%–57%, depending on engine speed. The application of both GTL diesel fuel and a Level 2 VDECS resulted in impressive, if not purely additive, reductions in PM of 48%–72%. The Thermo King pDPF Level 2 VDECS CARB verification is specific to TRU engine model years 2002 and older. This Level 2 verification requires a 50% reduction in PM from baseline conditions (OEM muffler). While measured PM reductions in this case are less than 50% for the low engine speed test condition, note that (a) the engine vintage tested (2004) is outside the engine vintage verified (2002 or older), and (b) the verification data are based on an eight-mode engine test cycle, rather than the steady-state conditions measured in situ. Also noteworthy is that, while raw PM emissions are much lower at low engine speed, the relative percentage decreases are larger at low engine speed than they are at high engine speed.

Reductions in NO_x were expected with GTL diesel but not expected with the Thermo King pDPF. Replacing CARB diesel with GTL diesel yielded NO_x reductions of 13%–16%, depending on engine speed. The ratio of NO/NO_2 was approximately the same across the two fuels. Replacing the OEM muffler with a Thermo King pDPF resulted in a slight increase in NO_x at high speed engine operation and a marginal decrease at low speed. The ratio of NO/NO_2 decreased at high engine speed (larger NO_2 fraction), but increased at low engine speed (smaller NO_2 fraction). The reason for this is unknown, although it can be presumed that low speed engine operation does not sufficiently light off the pDPF catalyst, resulting in a smaller oxidized NO_x (NO_2) fraction. The application of both GTL diesel fuel and a Level 2 VDECS resulted in a NO_x decrease of 12% at high engine speed, but an increase of 11% at low engine speed.

Reductions of CO and THC were expected with GTL diesel and generally expected with the pDPF because of its catalyzed nature. Replacing CARB diesel with GTL diesel yielded CO and THC reductions of 17%–19% and 22%–43%, respectively, depending on engine speed. Replacing the OEM muffler with a Thermo King pDPF resulted in CO and THC reductions of 66%–99% and 30%–96%, respectively, depending on engine speed. The application of both GTL diesel fuel and Level 2 VDECS resulted in dramatic CO and THC reductions of 98%–99% and 76%–97%, respectively, depending on engine speed.

Differences in measured fuel consumption were observed across the test configurations. These differences were generally unexpected in terms of both magnitude and direction. However, raw fuel consumption values (Table 3) are generally small, in the hundredths of a gallon per hour. These differences are likely within the measurement error of the experimental equipment. It is unlikely that these differences were a function of the TRU or GTL diesel fuel. The TRU tested utilizes an engine with mechanically direct fuel injection. Thus, there were no subtle changes in fuel injection volume and timing due to the application of GTL diesel, with its significantly higher cetane number and lower density.

CONCLUSIONS

These in situ tests characterize the emissions from integrated TRUs rather than just the diesel engine. This methodology may yield relevant real-world TRU emissions profiles, providing better insight into the contribution of TRUs to emissions inventories. Integration of emissions over a period of time, including relative weighting of high and low idle times, is a logical extension to this work.

The use of GTL diesel fuel as a replacement to CARB diesel fuel can reduce gaseous emissions and PM at both high and low engine speeds. Replacement of the stock muffler with a Thermo King pDPF can also reduce some gaseous emissions and PM at both high and low TRU engine speeds. Compounded reductions, significant in the case of CO and THC, were realized in combining GTL diesel fuel with the Thermo King pDPF.

While there is no concrete explanation for the relative directional inversion of measured NO_x and calculated NO_2 and NO/NO_2 ratio with a pDPF test condition, it is likely that low engine speed operation does not sufficiently raise the catalyst temperature to enable light off and high efficiency oxidation. However, further investigation is warranted.

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CONTACT

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ACRONYMS

API: American Petroleum Institute
ATCM: Airborne Toxic Control Measure
CARB: California Air Resources Board
CO: carbon monoxide
CO_2: carbon dioxide
DOE: U.S. Department of Energy
g/hr: grams per hour
gal/hr: gallons per hour
gph: gallons per hour
GTL: gas-to-liquid
HFID: heated flame ionization detector
hp: horsepower
mm: millimeter
NA: not applicable
NM: not measured
NO: nitric oxide
NO_x: oxides of nitrogen
NO_2: nitrogen dioxide
NREL: National Renewable Energy Laboratory
OEM: original equipment manufacturer
O_2: oxygen
PFSS: partial flow sampling system
PM: particulate matter
psi: pounds per square inch
rpm: revolutions per minute
SCAQMD: South Coast Air Quality Management District
SL: Stockton laboratory
tpd: tons per day
THC: total hydrocarbons
TRU: transport refrigeration unit
VDECS: verified diesel emission control strategy

APPENDIX

Component	Method	GTL Diesel	CARB Diesel (Specification)	Units
Total Acid	ASTM D974	<0.001		mgKOH/g
Appearance	ASTM D4176	1		
Di Aromatic H/C	IP 391/95	0		mass %
Mono Aromatic H/C		0		mass %
Poly Aromatic H/C		0	1.4 max	mass %
Total Aromatic H/C		0	10 max	mass %
Tri Aromatic H/C		0		mass %
Ash	ASTM D482	<0.01		mass %
Carbon Residue	ASTM D4530	0.01		mass %
Cetane Number	ASTM D613	81.0	48 min	
CFPP	ASTM D6371	-6		degC
Cloud Point	ASTM D2500	-4.4	2.2	degC
Colour Lovibond	ASTM D1500	0		
Total Contaminants	EN ISO 12662	3.1		mg/kg
Copper Corrosion	ASTM D130	1A		
Density @ 20	ASTM D4052	0.7708		kg/l
10%	ASTM D86	208.6	205 - 255	degC
20%		222.0		degC
30%		235.5		degC
40%		251.0		degC
5%		199.1		degC
50%		267.6	245 - 295	degC
60%		284.5		degC
70%		301.1		degC
80%		319.3		degC
90%		340.2	290 - 320	degC
95%		354.2		degC
FBP		362.5		degC
IBP		175.7	170 - 215	degC
Recovery		99.0		vol %
Flash Point	ASTM D93	68	54 min	degC
Lubricity	ASTM D6079	349		WSD micrometre
Oxidation Stability	ASTM D2274	0.4		mg/100ml
Total Sulphur	ASTM D5453	4	15 max	mg/kg
Viscosity @ 40 Kin	ASTM D445	2.54	2.0 - 4.1	cSt

REPORT DOCUMENTATION PAGE

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14. ABSTRACT *(Maximum 200 Words)*
A novel in situ method was used to measure emissions and fuel consumption of transport refrigeration units (TRUs). The test matrix included two fuels, two exhaust configurations, and two TRU engine operating speeds. Test fuels were California ultra low sulfur diesel and gas-to-liquid (GTL) diesel. Exhaust configurations were a stock muffler and a Thermo King pDPF diesel particulate filter. The TRU engine operating speeds were high and low, controlled by the TRU user interface. Results indicate that GTL diesel fuel reduces all regulated emissions at high and low engine speeds. Application of a Thermo King pDPF reduced regulated emissions, sometimes almost entirely. The application of both GTL diesel and a Thermo King pDPF reduced regulated emissions at high engine speed, but showed an increase in oxides of nitrogen at low engine speed.

15. SUBJECT TERMS
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