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Fuel Property, Emission Test, and Operability Results from a Fleet of Class 6 Vehicles Operating on Gas-To-Liquid Fuel and Catalyzed Diesel Particle Filters

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ABSTRACT

A fleet of six 2001 International Class 6 trucks operating in southern California was selected for an operability and emissions study using gas-to-liquid (GTL) fuel and catalyzed diesel particle filters (CDPF). Three vehicles were fueled with CARB specification diesel fuel and no emission control devices (current technology), and three vehicles were fueled with GTL fuel and retrofit with Johnson Matthey's CCRT™ diesel particulate filter. No engine modifications were made.

Bench scale fuel-engine compatibility testing showed the GTL fuel had cold flow properties suitable for year-round use in southern California and was additized to meet current lubricity standards. Bench scale elastomer compatibility testing returned results similar to those of CARB specification diesel fuel. The GTL fuel met or exceeded ASTM D975 fuel properties.

Researchers used a chassis dynamometer to test emissions over the City Suburban Heavy Vehicle Route (CSHVR) and New York City Bus (NYCB) cycles. The GTL- fueled vehicles were tested with and without the CDPFs to isolate fuel and aftertreatment effects.

All emission changes are compared to the CARB specification diesel baseline. Over the CSHVR cycle, GTL fuel (no filter) reduced all regulated emissions, with oxides of nitrogen (NO_x) reductions of 8% and particulate matter (PM) reductions of 33%. Over the NYCB cycle, GTL fuel (no filter) reduced NO_x and PM by 16% and 23%, respectively. Combining GTL and CDPF further reduced all regulated emissions, with NO_x and PM reductions of 14% and 99%, respectively, on the CSHVR cycle. Vehicles tested over the NYCB cycle on GTL fuel and CDPF produced NO_x and PM reductions of 20% and 97%, respectively.

INTRODUCTION

Gas-to-liquid (GTL) technology has been used for many years to synthesize hydrocarbons from natural gas. Recently, interest has grown in the production of GTL fuels and their emission reduction benefits. Several companies produce or have produced GTL fuels, including Shell, Sasol, ExxonMobil, and others.[1]

Many studies have examined the impact of GTL fuel on exhaust emissions from light- and heavy-duty vehicles and engines (summarized in Reference 2). In a majority of cases, GTL fuel produced a reduction in regulated emissions (hydrocarbons [HC], oxides of nitrogen [NO_x], carbon monoxide [CO], particulate matter [PM]) compared to conventional diesel fuel.

Much of the emission data reported have come from short-term studies, where the engine/vehicle has been switched to GTL fuel from conventional diesel fuel for the purposes of collecting emission test results. Upon concluding the tests, the engine/vehicle is then switched back to conventional diesel fuel. Thus, the long-term effect of GTL fuel on engine systems has not been adequately quantified.

FUEL PROPERTY TESTING

Previous studies of GTL diesel fuel do not always list complete fuel properties or test methods.[2] The fuel used in this study was tested to determine physical and chemical properties. In addition, researchers performed elastomer compatibility testing to characterize the impact of GTL fuel on fuel system elastomers.

FUEL PRODUCTION TECHNOLOGY – Shell Global Solutions (US) Inc. provided the fuel that was used for fuel property and emission testing, and on-road use.

The SMDS (Shell Middle Distillate Synthesis) process is well documented, so only a brief description is offered here.[3] The process is illustrated in Figure 1. The process was developed at Shell Research & Technology Centre Amsterdam and is comprised essentially of three stages:

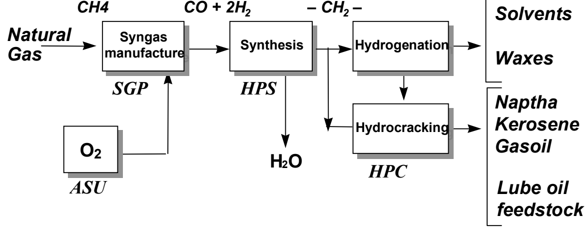
Manufacture of synthesis gas (hydrogen + carbon monoxide–with a H_2:CO ratio of approximately two) from natural gas by non-catalytic auto-thermal partial oxidation using, for example, the Shell Gasification Process.

Wax synthesis from CO + H_2 by Heavy Paraffin Synthesis (HPS), followed by flash distillation to separate light ends (e.g., liquefied petroleum gas).

Cracking of wax to distillates by Heavy Paraffin Conversion (HPC), where the boiling range and quality of the products can be adjusted to produce either kerosene or atmospheric gas oil (diesel).

A recent modification to this process, designated as SMDS-2 offers an improved HPS (Heavy Paraffin Synthesis) catalyst, which will enable the manufacturers to increase production capacity considerably. In addition, adjusting the severity in the hydrocracking/isomerization (HPC) stage allows control of the *n*- to *iso*- paraffin ratio in the final product.

Figure 1. Schematic illustration of Shell SMDS process.



FUEL PROPERTY TEST RESULTS - The fuel was tested for a wide range of properties, such as composition, energy content, cold flow properties, and elastomer compatibility. All fuel property testing was performed at Southwest Research Institute in San Antonio, TX.

Except for elastomer compatibility, which will be discussed separately, the test results are compiled in Table 1. Where applicable, the ASTM D975 specification is also listed.

The fuel composition was tested through elemental testing and hydrocarbon determination. GTL fuel is composed of carbon and hydrogen. The fuel H/C ratio is about 2.1, about 16% greater than conventional diesel fuel. The high H/C ratio is due to the near zero aromatic content of the GTL diesel fuel.[4] As with most GTL fuels, the Shell GTL has near zero sulfur content.

The very low aromatic content and/or the high H/C ratio of diesel fuel have been shown to reduce NO_x and PM emissions in previous studies.[5,6,7] Thus, testing with GTL fuel is likely to result in reductions in NO_x and PM emissions.

Fuel sulfur reductions also result in PM emission reductions, though with diminishing returns as sulfur content becomes very low.[6] In newer technology engines, the near zero sulfur content of GTL fuel may prove more beneficial by enabling sulfur sensitive emission control devices.

GTL fuels have reduced densities compared to conventional diesel fuels,[2] which have been shown to reduce the PM emission in older technology engines.[6,7] Low density fuels, such as GTL fuel, may alter the fuel mass flow rates.[7] Previous GTL fuel studies have not noted adverse effects on engine operation as a result of the lower fuel density.[9,10,11]

The cetane number of GTL fuels is most often reported as >74, much higher than conventional diesel fuels.[12] GTL fuel is composed almost wholly of paraffins. N-paraffins are known to have very high cetane numbers, while iso-paraffins have lower cetane numbers.[13]

Increasing cetane number has been linked to a decrease or no change in NO_x emissions. The effect appears to be depend on engine model year, with a less prominent effect on newer technology engines.[5,6,7]

Table 1. Fuel properties of Shell GTL fuel.

Property	**Test Method**	**Results**	**ASTM D975 Specification**
Density, g/mL	ASTM D4052	0.7838	
API Gravity	ASTM D287	49	
Viscosity, cSt at 40°C	ASTM D445	3.468	1.9-4.1
Flash Point, °C	ASTM D93	89	52 minimum
Sulfur, ppm	ASTM D5453	0.5	500 maximum
Carbon to Hydrogen ratio		2.13	
SFC Aromatics, mass%	ASTM D5186		
Monoaromatics		1.4	
Polynuclear aromatics		<0.1	
Total aromatics		1.4	
Hydrocarbon types, vol%	ASTM D1319		
Aromatics		1.0	35 maximum
Olefins		1.0	
Saturates		98.0	
Heat of combustion, BTU/lb	ASTM D240		
Gross		20,246	
Net		18,878	
Cetane Number	ASTM D613	79.5	40 minimum
	IQT	77.9	
Autoignition temperature, °C	ASTM E659	207.2	
Ignition delay time, seconds		141.3	
Distillation, °C	ASTM D86		
IBP		208.9	
T10		246.7	
T50		299.0	
T90		331.1	282-338
FBP		343.2	
Cloud Point, °C	ASTM D2500	1	
Pour Point, °C	ASTM D97	-6	
Cold filter plugging point (CFPP), °C	IP 309	-1	
Low temperature flow test (LTFT), °C	ASTM D4539	-2	
Water and Sediment	ASTM D1796	<0.02	--
Copper Corrosion	ASTM D130	1A	3 maximum
Peroxide number, mg/kg	ASTM D3703	<1	
Gum content, mg/100mL	ASTM D381	5.9	
Ash, mass%	ASTM D482	<0.001	0.01 maximum
Carbon residue, %mass	ASTM D524	0.03	0.15 maximum
Acid number, mg	ASTM D664	<0.5	
Accelerated stability, mg/100mL	ASTM D2274	0.4	
High temperature stability, 180 min, Avg % Reflectance	ASTM D6468	100	
Scuffing Load Ball-on-Cylinder Lubricity Evaluator, scuff load, g	ASTM D6078	2,750*	
High Frequency Reciprocating Rig, wear scar, mm	ASTM D6079	0.395*	

* Results from subsequent test.

Highly paraffinic GTL fuels may have cold flow properties that are not acceptable for operation throughout the United States. The test fleet in this project operated exclusively in southern California (metro Los Angeles area), where the cold flow operability of GTL fuel was not an issue.

Other properties, such as gum, ash, and water and sediment are in line with other diesel fuels and are not expected to impact operations. A reduced T90/T95 temperature has been shown to have a small impact on emissions.[7,14] For GTL fuel, any impact based on T90/T95 temperature is likely obscured by other fuel properties such as paraffin content and cetane number.

Typically, unadditized GTL fuels have poor lubricities due to a lack of polar molecules, but respond well to additives.[9,15] The fuel used in this work was additized.

BENCH ELASTOMER COMPATIBILITY TEST RESULTS – Bench scale elastomer testing was used to complement the real-world data gathered from introduction of GTL fuels into a vehicle fleet for many months.

International Truck and Engine Corporation contributed several sets of new elastomers for the compatibility testing. The elastomers were from the DT466 engine and were identical to those found in the study vehicles. The GTL fuel had the properties listed in Table 1. The commercial CARB specification diesel fuel was a typical diesel fuel meeting CARB diesel specifications. Properties for this fuel are in Table 2.

Table 2. CARB specification diesel fuel properties used for elastomer testing.

Property	Test Method	Results
Density, g/mL	ASTM D4052	0.8299
API Gravity	ASTM D287	38.9
Flash Point, °C	ASTM D93	70
Sulfur, ppm	ASTM D5453	153
Carbon, mass%	ASTM D5291	86.42
Hydrogen, mass%		13.64
Oxygen, mass% by difference		<0.01
SFC Aromatics, mass%	ASTM D5186	
Polynuclear Aromatics		3.4
Total Aromatics		21.8
Hydrocarbon types, vol%	ASTM D1319	
Aromatics		22.3
Olefins		2.7
Saturates		75.0
Heat of Combustion, BTU/lb	ASTM D240	
Gross		19,749
Net		18,505
Cetane Number	ASTM D613	55.4
Cloud Point, °C	ASTM D2500	-9
Pour Point, °C	ASTM D97	-26
Distillation, °C	ASTM D86	
IBP		176.4
T10		201.8
T50		261.4
T90		323.6
FBP		348.4
Gum Content, mg/100mL	ASTM D381	13.2

Elastomer testing included hardness, volume, radial thickness changes, elongation, reversion, bend testing, and sediment observation. Three identical elastomers were used for each test, under each of the three test conditions in addition to a set for the control case (no fuel exposure). The elastomers were in new, unused condition prior to the start of the tests.

1. CARB specification diesel fuel at 60°C for 1,000 hours
2. GTL fuel at 60°C for 1,000 hours
3. CARB diesel fuel at 60°C for 500 hours, followed by GTL fuel at 60°C for 500 hours, 1,000 hours total

The CARB specification diesel fuel exposure followed by GTL fuel exposure was selected to investigate the effect of changing fuels on elastomer properties. The impact of diesel fuel aromatic compounds on the swell of elastomers has been previously documented.[16] Diesel fuel properties may have a lesser effect on fluorocarbon elastomers than gasoline, but investigation is still needed. [17]

Four types of elastomers were tested and indicated as A, B, C1, and C2. Elastomer A was a seal, composed of Viton, VA-154-95. Elastomers B and C1 were also seals, composed of Viton, VA-153-90. Elastomer C2 was a cushion, composed of hydrogenated nitrile buna rubber (HNBR). The control results were collected from elastomers not exposed to fuel.

Results of the bench scale elastomer testing are in Appendix A-1. After exposure to the fuel(s), no sediment was recorded for any of the four types of elastomers, nor was any reversion observed. The elastomers also all passed the bend test. The reported hardness changes were minor for all four elastomers under each of the three test conditions.

Elastomers A, B, and C1 did not show an appreciable change in volume after exposure to any of the test fuels. Elastomer C2 showed some swelling upon exposure to the CARB specification diesel fuel, likely due to the 22% aromatic content of the fuel. However, no swelling was observed for C2 during exposure to the GTL alone or the CARB specification diesel followed by the GTL fuel.

The radial thickness of the elastomers did not change with exposure to the test fuels. This is an interesting point to note, as elastomer C2 swelled with exposure to the CARB specification diesel fuel. The increase in volume of elastomer C2 was not swelling along the radial axis, but an increase in the height of the elastomer.

A simple statistical analysis was performed on the elongation results. The results were analyzed using a two-tailed t-test, assuming equal variances, at the 95% confidence level. The p-values are shown in Table 3. Note that the symbol CARB→GTL indicates exposure to condition 3 or CARB specification diesel followed by GTL fuel.

There were no significant changes in the elongation of elastomer A, either compared to the control or between the fuels. For the most part, no changes in the elongation of elastomer B were observed. However, between the control and the GTL fuel and the control and the CARB specification diesel, small changes in the elongation for elastomer B were noted. No changes were recorded for C1.

For C2, only one small change was recorded for the CARB specification diesel compared to the CARB→GTL exposure. Elastomer C2 showed a higher overall variability compared to the other elastomers, possibly due to the chemical composition of the HNBR. Unfortunately, more detailed information about the degree of hydrogenation and acetonitrile content of C2 is not available.

All four elastomers held up well to the bench testing that was performed in this study. Based on the results from this portion, there was little concern about introducing the GTL fuel to the fleet vehicles. Additionally, no vehicle preparation was performed prior to the switch, such as replacing the elastomers.

Table 3. P-values for elastomer elongation results.

Elastomer	Fuels	P-value	Significant?
A	Control to GTL	0.407	No
A	Control to CARB →GTL	0.289	No
A	Control to CARB	0.348	No
A	GTL to CARB→GTL	0.896	No
A	GTL to CARB	0.993	No
A	CARB→GTL to CARB	0.889	No
B	Control to GTL	0.033	Yes
B	Control to CARB→GTL	0.251	No
B	Control to CARB	0.059	Maybe
B	GTL to CARB→GTL	0.187	No
B	GTL to CARB	0.776	No
B	CARB→GTL to CARB	0.306	No
C1	Control to GTL	0.818	No
C1	Control to CARB→GTL	0.556	No
C1	Control to CARB	0.678	No
C1	GTL to CARB→GTL	0.132	No
C1	GTL to CARB	0.346	No
C1	CARB→GTL to CARB	0.864	No
C2	Control to GTL	0.745	No
C2	Control to CARB→GTL	0.137	No
C2	Control to CARB	0.745	No
C2	GTL to CARB→GTL	0.013	Yes
C2	GTL to CARB	0.264	No
C2	CARB→GTL to CARB	0.043	Yes

FLEET PROPERTIES

Yosemite Waters in Fullerton, CA provided the study vehicles for this project. The participating vehicles were similar and operated out of a single location. Vehicle and engine specifications are shown in Table 4.

Each Yosemite Waters vehicle operates on a dedicated 10-day route with varying degrees of city and freeway driving. Thus, the driving characteristics of each vehicle were somewhat unique (see Table 5). Also shown in Table 5 are the vehicles selected to operate on CARB specification diesel fuel and the vehicles selected to operate on GTL fuel with the emission control devices.

One factor in designating the vehicles as “baseline” or “test” was the percentage of highway miles. Vehicles 201 and 204 have the lowest percentage of highway miles. If these vehicles were both “baseline” or both “test”, the real-world fuel economy might be biased, as lower fuel economy is recorded during city driving. Thus, vehicle 201 was in the “baseline” group and vehicle 204 was in the “test” group.

Table 4. Vehicle and engine specifications for Yosemite Waters test fleet.

Vehicle	
Manufacturer	International
Model number	4300-DT466
Body manufacturer	Hackney
Vehicle activity	Pickup and delivery
Transmission type	5-speed automatic
Transmission manufacturer	Allison
Transmission Model	2000
Engine	
Manufacturer	International
Engine	DT466
Configuration	Inline 6 cylinder
Model year	2001
Peak Power	195 hp @ 2,300 rpm
Peak Torque	520 ft-lb

Table 5. Driving characteristics for test vehicles in Yosemite Waters fleet.

Vehicle	Fuel/ Emission Control	% Highway Miles over 10-day cycle	Total Miles Driven over 10-day cycle
201	CARB, None	36	532
202	CARB, None	75	752
203	CARB, None	74	1,030
204	GTL, CCRT filter	61	680
205	GTL, CCRT filter	82	667
206	GTL, CCRT filter	77	837

The other vehicles had more similar percentages of highway miles and were divided so that consecutive vehicle numbers were in the same category (i.e. 201, 202, and 203 were baseline).

EMISSION CONTROL DEVICES

The test vehicles were operated on GTL fuel for at least two weeks prior to installing the emission control devices to ensure no residual CARB specification diesel fuel remained in the fuel system.

Johnson Matthey supplied the emission control devices– CCRT filters (Catalyzed Continuously Regenerating Technology). The CCRT filter is a diesel oxidation catalyst followed by a wall-flow catalyzed soot filter.[22] Testing has shown that the CCRT filter has good low temperature performance.

The good low temperature performance was an important characteristic in selecting the CCRT filter for this project. Because vehicle 204 had a low percentage of highway miles compared to the other fleet vehicles and subsequently, a low average exhaust temperature (average exhaust temperature ~ 210°C), it was selected to be the first vehicle retrofit.

The exhaust temperature and pressure of vehicle 204 was monitored for several months to insure the filter performance was acceptable. Exhaust pressure and temperature histograms collected over several months showed stable filter operation. After analyzing this data, vehicles 205 and 206 were retrofit as well.

DATALOGGER RESULTS

On-board dataloggers were used to evaluate the efficacy of the CCRT filters by continuously measuring exhaust backpressure and temperature over the road.

As shown in Table 5, vehicle 204 travels on the highway 61% of the time during its 10-day route. Of the three test vehicles, the average exhaust temperature of this vehicle is expected to be the lowest. Figure 2 presents a histogram of the data collected from vehicle 204 during the project. The shaded area indicates that the vehicle has an exhaust temperature above about 210°C for 40% of its operating time. Similar histograms are shown in Figures 3 and 4 for vehicles 205 and 206. The 40% cut-point temperature for vehicles 205 and 206 is much higher than for vehicle 204 (~230°C and ~240°C, respectively).

Figure 2. Exhaust temperature histogram for vehicle 204 from January 2003 through June 2004.

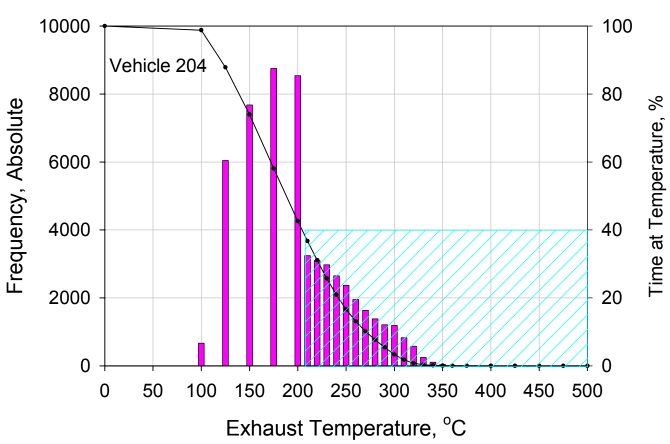


Figure 3. Exhaust temperature histogram for vehicle 205 from December 2003 through June 2004.

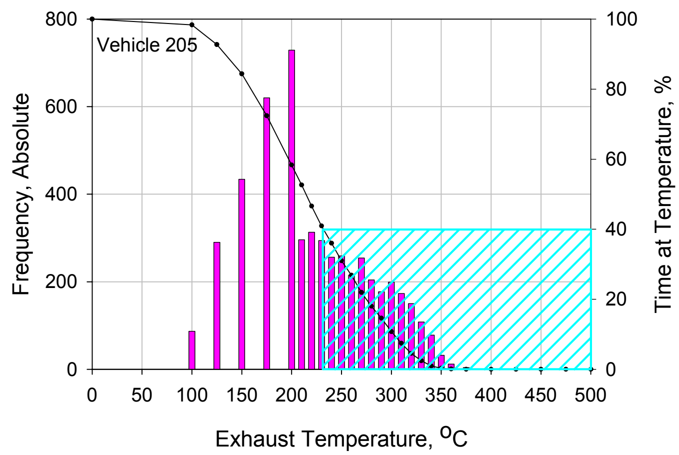
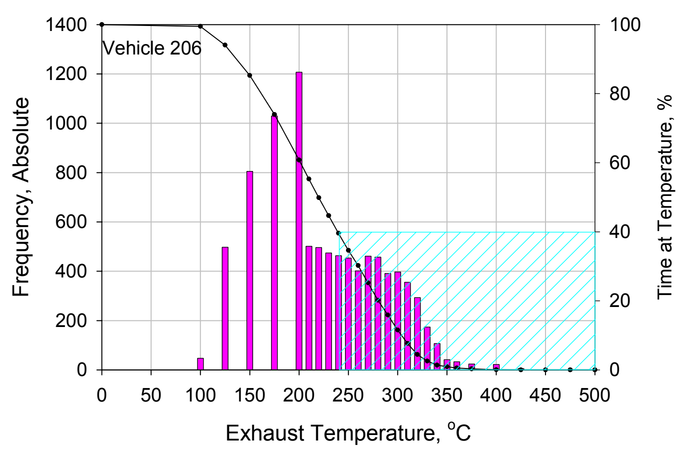


Figure 4. Exhaust temperature histogram for vehicle 206 from December 2003 through June 2004.



The peak exhaust backpressure data can be used to show if filter performance is deteriorating over time. As the filter becomes plugged, the peak backpressure should increase. Figures 5, 6, and 7 illustrate the peak backpressure for Yosemite Waters vehicles 204, 205, and 206. The backpressure has been very constant over the study period, indicating good filter operation.

Figure 5. Peak backpressure for vehicle 204 from January 2003 through June 2004.

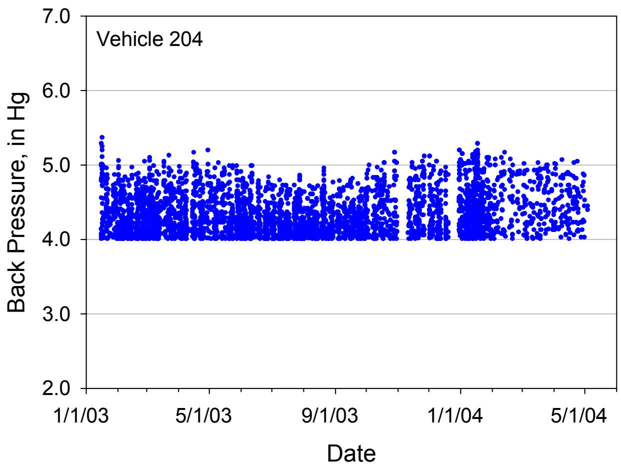


Figure 6. Peak backpressure for vehicle 205 from December 2003 through June 2004.

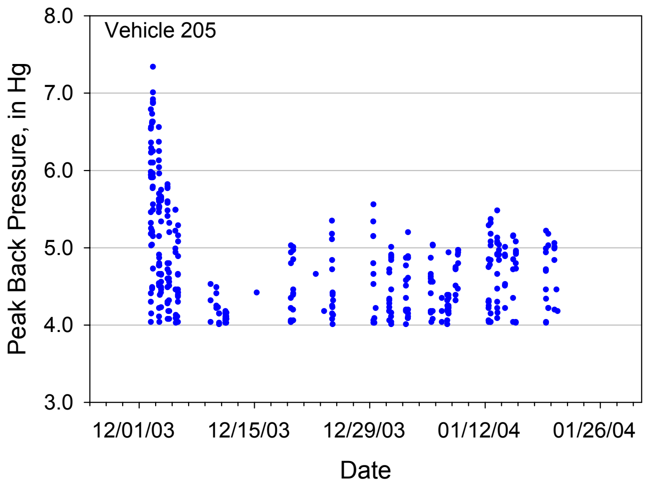
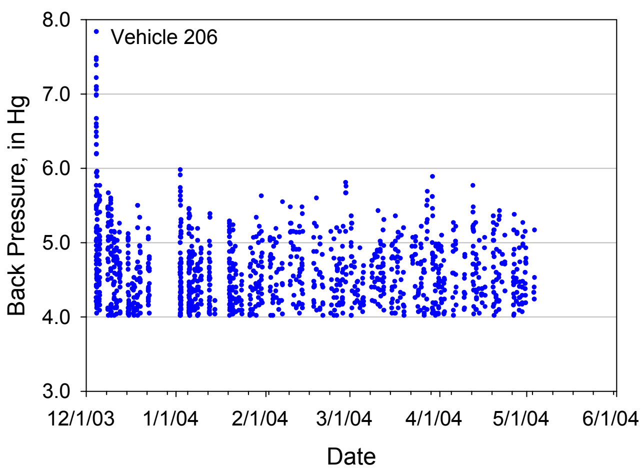


Figure 7. Peak backpressure measurements for vehicle 206 from December 2003 through June 2004.



CHASSIS EMISSION COLLECTION

West Virginia University collected chassis exhaust emissions for the six study vehicles. The West Virginia University Transportable Vehicle Emissions Testing Laboratories were constructed to gather emissions data from in-use heavy-duty vehicles. Detailed information pertaining to the design and operation of the laboratories has been previously published.[18,19,20]

Each laboratory is based around two trailers, one trailer contains rollers, flywheels, and power absorbers for the dynamometer function, and the second trailer houses the controls and emissions measurement equipment. The vehicle to be tested is driven onto the chassis dynamometer and positioned on two sets of rollers (Figure 8). The outer wheels of the dual wheel set on each side of the vehicle are removed and replaced with hub adapters that couple the drive axle directly to the dynamometer units on each side of the vehicle. (See Figure 9).

Each dynamometer unit consists of a power absorber and a set of selectable flywheels, which consist of a series of discs to allow simulation of an inertial load equivalent to a gross vehicle weight of up to 60,000 pounds in 250 pound increments. During the test cycle, torque cells and speed transducers in the power absorber drive train measure the vehicle load and speed. The vehicle can be driven through a wide range of available computerized test cycles to simulate either transient or steady state driving conditions.

Figure 8. Photo of Yosemite Waters Vehicle No. 201 on WVU Transportable Vehicle Emissions Testing Laboratory.

Figure 9. Close-up photo of hub adapters coupled to drive axle.

The exhaust from the tail pipe of the test vehicle is ducted to a full-scale dilution tunnel measuring 45cm in diameter and 6.1m in length. The exhaust is mixed with air and the quantity of diluted exhaust is measured precisely by a critical flow venturi system (CVS).

The diluted exhaust is analyzed using non-dispersive infra-red analyzers for CO and CO_2, and chemiluminescent detection for NO_X. Hydrocarbons are analyzed using a heated flame ionization detector. The gaseous data are available as continuous concentrations throughout the test, and the product of concentration and dilution tunnel flow are integrated to yield emissions in units of grams per mile (g/mi). Particulate matter is collected using 70-mm fluorocarbon coated glass fiber filter media and is determined gravimetrically. Fuel efficiencies are determined using a carbon balance and exhaust emissions data.

Vehicles were tested over a two-week period in December 2003. The test matrix is shown in Table 6. Testing was conducted over two cycles–the City Suburban Heavy Vehicle Route (CSHVR) and the New York City Bus Cycle (NYCB). The cycles designated by (2) indicate the cycle was run as a “double”. In a “double” cycle, the original test cycle is run twice, back-to-back without interruption, on a single set of filter media. This ensures that an adequate mass of PM is collected for measurement.

The CSHVR cycle, shown in Figure 10, is a highly transient cycle with about 10% of the cycle spent at idle conditions. In contrast, the NYCB cycle (Figure 11) spends over 65% of the cycle at idle, with much less transient driving. These cycles were selected to test the fuel and emission control systems over a highly transient and a stop-and-go type cycle (CSHVR and NYCB, respectively).

Table 6. Vehicle matrix for chassis dynamometer testing.

Vehicle	Fuel/Emission Control	Cycle 1	Cycle 2
201	CARB, None	CSHVR	NYCB
202	CARB, None	CSHVR	NYCB
203	CARB, None	CSHVR	NYCB
204	GTL, None	CSHVR	NYCB
204	GTL, CCRT filter	CSHVR(2)	NYCB(2)
205	GTL, None	CSHVR	NYCB
205	GTL, CCRT filter	CSHVR(2)	NYCB(2)
206	GTL, None	CSHVR	NYCB
206	GTL, CCRT filter	CSHVR(2)	NYCB(2)

Figure 10. Schematic of CSHVR driving cycle.

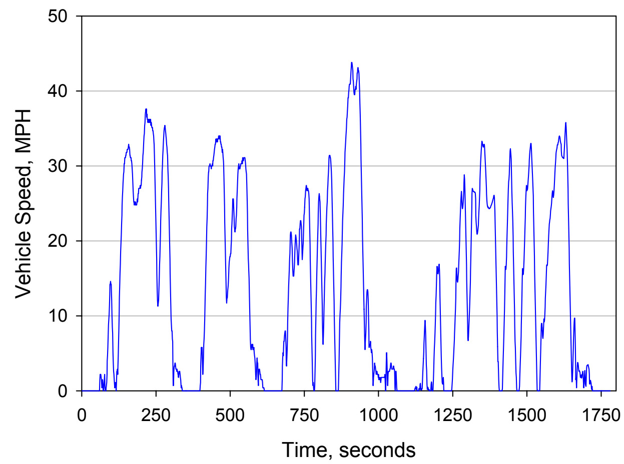
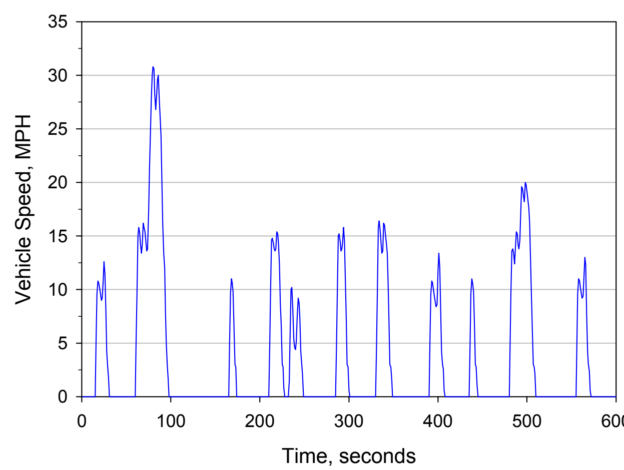


Figure 11. Schematic of NYCB driving cycle.



EMISSIONS RESULTS

Detailed emission test results are presented in Appendix A-2. Vehicle 204 operated with the CCRT filter for 11 months (January 2003 through December 2003). Vehicles 205 and 206 were retrofit in early December 2003. The emission results for the GTL fuel with the

CCRT filter will be discussed as the average over all three vehicles.

The error bars on the following figures are one confidence interval. The error bars on these figures were generated from the estimated emissions as part of the statistical analysis described in Appendix A-3. Statistical significance of the emission results will be presented later in this paper. Statistical significance of the emissions should not be estimated by overlap of the error bars presented in the figures.

REGULATED EMISSIONS

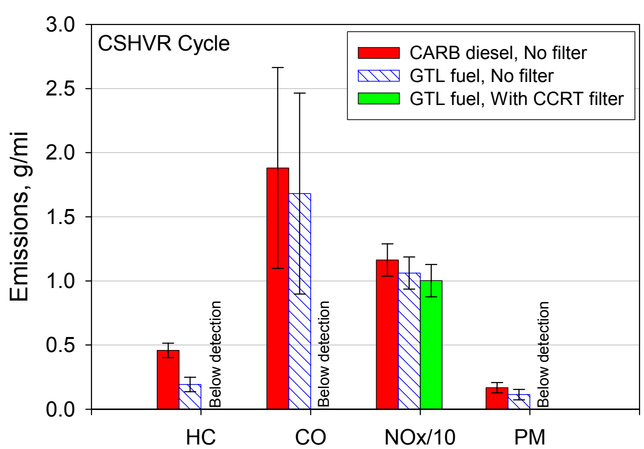
CSHVR cycle – Tests conducted with the CARB specification diesel fuel served as the baseline for these results. Changing to GTL fuel (no filter or engine out) from the CARB specification diesel fuel resulted in reductions of all regulated emissions. HC and CO emission reductions were 58% and 10.6%, respectively (see Figure 12).

A 33% reduction in the PM emission was recorded. Researchers expect that the reduction in the PM emission was due to a reduction in the soot portion of the PM, as noted in previous work.[21] A NO_x emission reduction of 8.8% was observed with the GTL fuel (engine out) compared to the CARB specification diesel fuel (engine out). This reduction is in line with previous estimates for GTL fuel in diesel engines.[0]

Combining the GTL fuel with the CCRT filter resulted in larger emission reductions for the regulated pollutants. The average reductions in HC, CO, and PM for all three vehicles (204, 205, and 206) were greater than 99%.

With the CCRT filter, the NO_x emissions were reduced 14% compared to CARB specification diesel fuel tests. This reduction is likely due to conversion of a small amount of NO_2 to N_2 over the filter.[22]

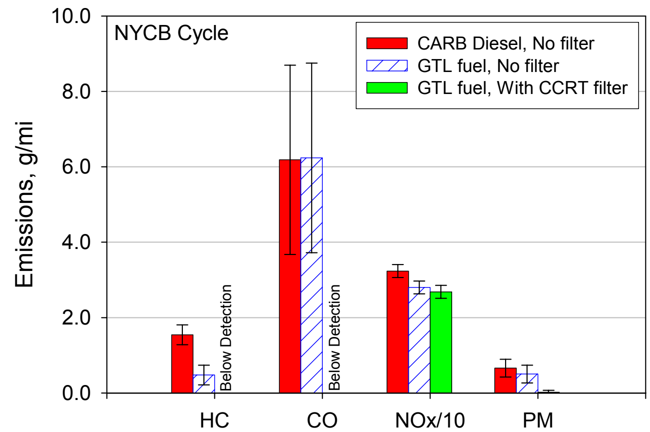
Figure 12. CSHVR Regulated Emissions Results.



NYCB Test Results – As with the CSHVR cycle, all results are compared to the CARB specification diesel fuel baseline. Over the NYCB cycle, there was no change in the CO emission (+0.81%), but large reductions in HC and PM emissions (69% and 23%, respectively). The NO_x emissions were reduced by 13% over the NYCB cycle. The emissions results are illustrated in Figure 13.

The effect of the GTL fuel and the CCRT filter on emissions was significant. HC and CO emissions were reduced to below detection limits. A 97% reduction in the PM emission was recorded. A slight additional NO_x decrease was detected (17% reduction compared to baseline), attributed to the NO_2 to N_2 conversion.

Figure 13. NYCB Regulated Emissions Results.



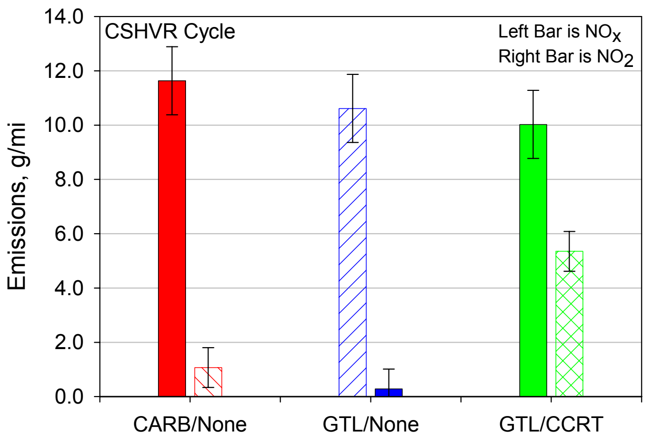
CALCULATED NO_2 EMISSIONS

The NO_2 emissions were calculated using a dual NO_x analyzer method. The method employs two unique NO_x analyzers, one operated in the NO_x mode, while the other analyzer operates in the NO mode. The difference between NO_x emission and NO emission is the calculated NO_2 emission. The technique and limitations have been previously described.[23] In Figures 14 and 15, the shaded bar on the left represents the calculated NO_2 emission, while the solid bar on the right shows the NO_x emission. The error bars are the confidence interval, as described above.

CSHVR CYCLE – Figure 14 presents the NO_x and calculated NO_2 emissions from the Yosemite Waters vehicles over the CSHVR cycle. As illustrated in the figure, the calculated NO_2 for the testing without the CCRT filter is similar for the CARB specification diesel and GTL fuels and is a very small portion of the total NO_x emission. A substantial increase of almost 50% of the NO_x emission in the calculated NO_2 emissions is observed with the CCRT filter.

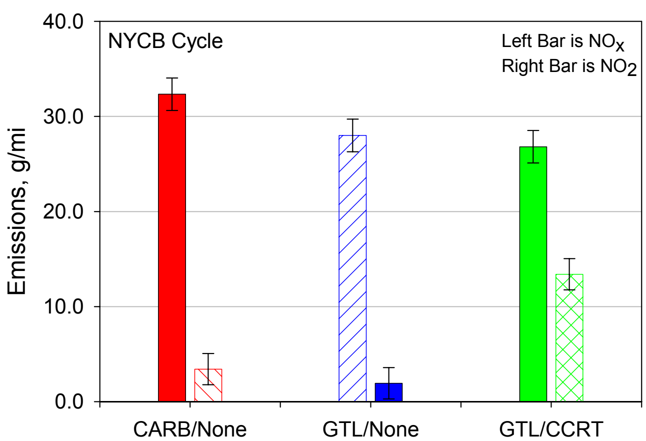
The increase in calculated NO_2 with the CCRT filter was expected. These types of emission control devices continuously oxidize NO to NO_2, which reduces the exhaust temperature needed to regenerate PM collected on the filter. With the very low average exhaust temperatures of this fleet, a highly active emission control device was selected, which is very active for NO_2 production.

Figure 14. NO_x and Calculated NO_2 emissions for the CSHVR cycle.



NYCB Cycle – Similar trends in the calculated NO_2 emissions are observed in the NYCB cycle (Figure 15). The calculated NO_2 comprises a very small portion of the total NO_x emission for the GTL fuel and CARB specification diesel fuel. The presence of the CCRT filter substantially increases the calculated NO_2 emission to roughly 50% of the total NO_x emission.

Figure 15. NO_x and Calculated NO_2 emissions for the NYCB cycle.



FUEL ECONOMY

CSHVR Cycle – The fuel economy is calculated from the CO_2 emission and reported in miles per gallon (mpg). As shown in Figure 16 (CSHVR Cycle), there is very little difference between the fuels, with or without the emission control devices. The error bars on the following figures are one confidence interval, using the methods previously described and in Appendix A-3.

NYCB Cycle – Figure 17 presents the fuel economy for the vehicles over the NYCB cycle. As with the CSHVR cycle, the measured fuel economy does not change with GTL fuel, with and without the CCRT, compared to the CARB specification diesel.

Figure 16. Measured fuel economy over the CSHVR cycle.

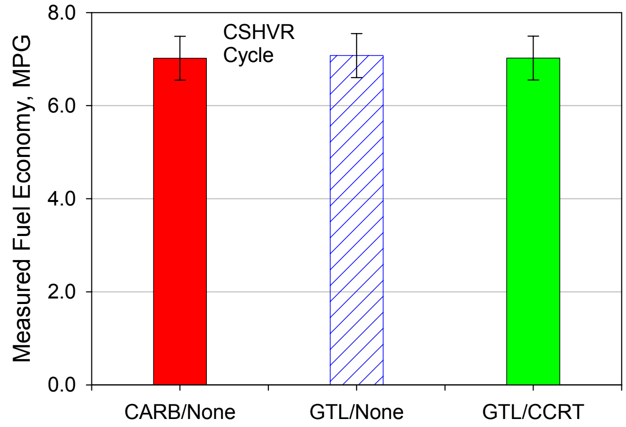
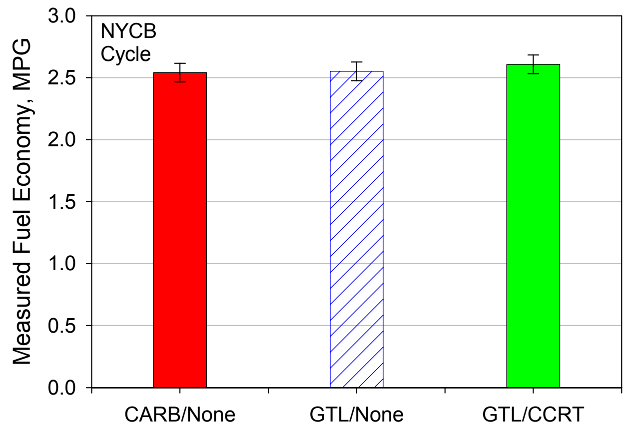


Figure 17. Measured fuel economy over the NYCB cycle.



STATISTICAL ANALYSIS OF EMISSION RESULTS

A rigorous statistical analysis of the emission results was performed to determine the significance of the emission reductions observed with the GTL fuel with and without the CCRT filter compared to the CARB specification diesel fuel. A detailed analysis of the statistical method is in Appendix A-3.

CSHVR Cycle – The statistical analysis shows that although there is a NO_x reduction of almost 9% with the GTL fuel (no filter), this difference is not statistically significant at the 95% confidence level. The CO and PM emission reductions are also not significant at the 95% confidence level, although the HC emission reduction is significant. There was no impact on the fuel economy with the GTL fuel and/or the CCRT filter compared to the CARB specification diesel fuel.

As expected, the CCRT filter and the GTL fuel caused significant reductions in the HC, CO, and PM emissions. The small additional NO_x reduction observed with the filter was not significant, compared either to the CARB specification diesel fuel or the GTL fuel without the filter.

The calculated NO_2 emissions were increased significantly with the CCRT filter, compared to both the CARB specification diesel and the GTL fuel without the filter. This result was expected. Calculated NO_2 emissions for the CARB specification diesel fuel, no filter, and the GTL fuel, no filter, were not calculated. The dual-NO_x analyzer technique employed in this work was not sufficiently robust to distinguish between the very low levels of NO_2 emitted from vehicles without emission control devices.

Table 7 shows which emission reductions are significant based on this analysis. "Yes" indicates that the change between fuel and/or filter technology is significant at the 95% confidence level, while "No" indicates the change is not significant. "NA" means that no comparison was possible. The directional arrows indicate whether the second fuel/filter combination increased (↑), decreased (↓), or made no change (↔) in the emissions.

Table 7. Statistical Significance of Emissions Changes from Yosemite Waters Vehicles over the CSHVR Cycle.

Comparison	HC	CO	NO_x	NO_2	PM	MPG
CARB/No Filter vs. GTL/No Filter	Yes ↓	No ↓	No ↓	NA	No ↓	No ↔
CARB/No Filter vs. GTL/CCRT Filter	Yes ↓	Yes ↓	No ↓	Yes ↑	Yes ↓	No ↔
GTL/No Filter vs. GTL/CCRT Filter	Yes ↓	Yes ↓	No ↓	Yes ↑	Yes ↓	No ↔

<u>NYCB Cycle</u> – The NO_x emission reduction that was observed with the GTL fuel, no filter, over the NYCB cycle was statistically significant (13%). When comparing the emissions of the CARB specification diesel fuel and the GTL fuel, both without the filter, only the HC emission reduction was also significant (PM and CO emission reductions were not significant). The fuel economy over the test cycle did not change significantly with the GTL fuel compared to the CARB specification diesel fuel.

With the GTL fuel and the CCRT filter, all the emissions were reduced significantly compared to the CARB specification diesel fuel. The same results were observed when comparing the GTL fuel with and without the filter – all the emission reductions were significant at the 95% confidence level. Again, the fuel economy did not change significantly.

As with the CSHVR cycle, the calculated NO_2 increased significantly with the CCRT filter, compared to testing without the filter. Statistical significance of the CARB/No filter and GTL/no filter was not tested due to the lack of robustness of the analysis technique for calculated NO_2 emissions.

In the same format at Table 7, Table 8 shows the emission reductions over the NYCB cycle. Again, "NA" indicates that no comparison was made for these pollutants.

It should be noted that these results are only for this vehicle fleet, tested over the CSHVR and NYCB cycles.

Table 8. Statistical Significance of Emissions Changes from Yosemite Waters Vehicles over the CSHVR Cycle.

Comparison	HC	CO	NO_x	NO_2	PM	MPG
CARB/No Filter vs. GTL/No Filter	Yes ↓	No ↔	Yes ↓	NA	No ↓	No ↔
CARB/No Filter vs. GTL/CCRT Filter	Yes ↓	Yes ↓	Yes ↓	Yes ↑	Yes ↓	No ↔
GTL/No Filter vs. GTL/CCRT Filter	Yes ↓	Yes ↓	Yes ↓	Yes ↑	Yes ↓	No ↔

CONCLUSIONS

Six 2001 International Class 6 trucks were selected for an operability and emissions study. Three vehicles were "baseline" vehicles, tested with CARB specification diesel fuel and no emission control devices. Three vehicles were operated on GTL fuel and retrofit with Johnson Matthey CCRT filters.

Prior to introduction into the fleet, the GTL fuel used in this study was subjected to extensive bench scale fuel property testing. The GTL fuel met or exceeded the ASTM D975 property specifications for low-sulfur diesel fuel.

Bench elastomer compatibility results showed that the fuels affected the elastomers equally. The results from the testing did not indicate potential problems when changing from CARB specification diesel fuel to GTL fuel. The change from CARB specification diesel fuel to the GTL fuel in the test vehicles was an overnight switch, with no vehicle preparation. No reports of elastomer compatibility issues (leaks, more frequent hose replacement, etc.) have been raised since the fuel change.

Once the vehicles were operating on GTL fuel, they were retrofit with Johnson Matthey CCRT filters. The vehicles were then put back into normal fleet operation. Data from on-board dataloggers show stable filter operation over the study period.

Chassis dynamometer emission testing was used to quantify the emission reductions with the GTL fuel and the CCRT filters. The GTL fueled vehicles were tested with and without the CCRT filters. Results show that:

- The GTL fuel (no filter) reduced regulated emissions over the CSHVR and NYCB cycles, compared to CARB specification diesel fuel. Emission reductions over the CSHVR cycle were 58% for HC, 10% for CO, 8% for NO_x, and 33% for PM. Only the HC emissions reductions were significant at the 95% confidence level.

  Emission reductions over the NYCB cycle were 69% for HC, 13% for NO_x, and 23% for PM. A slight CO increase was noted (0.8%). The NO_x and HC emissions reductions were statistically significant.

  The fuel economy did not change significantly over either test cycle, with any of the changes in fuel and/or emission control technologies.

- By combining the GTL fuel with the CCRT filter, even larger emission reductions were observed over both test cycles.

  Emission reductions were over 99% for HC, CO, and PM, with a NO_x reduction of 14% for the CSHVR cycle. Significant emission reductions were observed for the HC, CO, and PM.

  Testing over the NYCB cycle with the CCRT filter resulted in reductions greater than 97% for HC, CO, and PM. NO_x emissions were reduced were 17%. At the 95% confidence level, reductions were statistically significant for HC, CO, PM, and NO_x.

  As expected, the CCRT filter increased the calculated NO_2 emissions from very low to almost 50% of the total NO_x emission, regardless of test cycle. The increase in calculated NO_2 emissions was statistically significant for both the CSHVR and NYCB cycles.

The Yosemite Waters vehicles operated on GTL fuel with the CCRT filters through July 2004, accumulating between 10,000 and 24,000 miles. The fleet has not reported any problems with the change from CARB specification diesel to GTL fuel and the CCRT filters. To quantify the fleet experience, a thorough analysis of the maintenance records will be performed and reported in a future publication.

ACKNOWLEDGMENT

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ABBREVIATIONS

ASTM: American Society of Testing and Materials
CARB: California Air Resources Board
CCRT: Catalyzed Continuously Regenerating Technology
CDPF: Catalyzed diesel particulate filter
CO: Carbon monoxide
CO_2: Carbon dioxide
CSHVR: City Suburban Heavy Vehicle Route
°C: Degree Centigrade
g/mi: Grams per mile
g/mL: Grams per mililiter
GTL: Gas-to-liquid
HC: Hydrocarbons
HNBR: Hydrogenated nitrile buna rubber
HPC: Heavy Paraffin Conversion
HPS: Heavy Paraffin Synthesis
mpg: Miles per gallon
N_2: Atomic nitrogen
NO_2: Nitrogen dioxide
NO_x: Oxides of nitrogen
NYCB: New York City Bus
PM: Particulate matter
SMDS: Shell Middle Distillate Synthesis

APPENDIX A-1.

Elastomer Compatibility Results.

Test Parameter	Elastomer A		Elastomer B		Elastomer C1		Elastomer C2	
CARB Specification Diesel 60°C for 1,000 Hours								
Hardness Change								
Seal 1	+2		+1		-2		+1	
Seal 2	+2		0		-3		+1	
Seal 3	+2		+1		-2		+1	
% Volume Change								
Seal 1	+2.71		+2.11		+2.39		+14.93	
Seal 2	+2.69		+2.16		+2.56		+14.45	
Seal 3	+2.56		+2.22		+2.47		+14.28	
Reversion	No reversion		No reversion		No reversion		No reversion	
Bend Test	Pass		Pass		Pass		Pass	
Radial Thickness	Before	After	Before	After	Before	After	Before	After
Seal 1	3.13	3.17	3.44	3.51	3.04	3.17	2.64	2.50
Seal 2	3.12	3.16	3.45	3.51	3.06	3.17	2.66	2.51
Seal 3	3.11	3.16	3.44	3.49	3.05	3.17	2.64	2.50
Sediment Observation	None Observed		None Observed		None Observed		None Observed	
GTL Fuel 60°C for 1,000 Hours								
Hardness Change								
Seal 1	+2		+1		-2		+3	
Seal 2	+2		+1		-2		+3	
Seal 3	+2		+1		-2		+3	
% Volume Change								
Seal 1	+1.67		+1.49		+1.56		-0.66	
Seal 2	+2.01		+1.49		+1.80		-0.51	
Seal 3	+2.19		+1.50		+2.04		+0.25	
Reversion	No reversion		No reversion		No reversion		No reversion	
Bend Test	Pass		Pass		Pass		Pass	
Radial Thickness	Before	After	Before	After	Before	After	Before	After
Seal 1	3.12	3.16	3.46	3.46	3.05	3.17	2.63	2.62
Seal 2	3.13	3.16	3.45	3.46	3.06	3.17	2.63	2.63
Seal 3	3.13	3.17	3.45	3.46	3.05	3.17	2.64	2.63
Sediment Observation	None observed		None observed		None observed		None observed	
CARB Specification Diesel 60°C for 500 Hours→ GTL Fuel 60°C for 500 Hours								
Hardness Change								
Seal 1	0		0		0		0	
Seal 2	0		0		0		+1	
Seal 3	0		0		0		0	
% Volume Change								
Seal 1	+1.17		+0.57		+0.50		-1.23	
Seal 2	+1.10		+0.74		+0.65		-0.98	
Seal 3	+1.03		+0.99		+0.68		-0.77	
Reversion	No reversion		No reversion		No reversion		No reversion	
Bend Test	Pass		Pass		Pass		Pass	
Radial Thickness	Before	After	Before	After	Before	After	Before	After
Seal 1	3.13	3.23	3.44	3.45	3.05	3.11	2.66	2.54
Seal 2	3.14	3.23	3.45	3.46	3.06	3.12	2.65	2.52
Seal 3	3.12	3.22	3.44	3.45	3.06	3.11	2.66	2.53
Sediment Observation	None observed		None observed		None observed		None observed	

APPENDIX A-1.

Elastomer Compatibility Results (con't).

Elastomer Type	Condition	Inside Diameter	O-ring Thickness	Inside Circumference	Extension at Break	Elongation	Average Elongation
		(in)	*(in)*	*(in)*	*(in)*	*(%)*	*(%)*
A	Control	1.23	0.123	3.8622	2.611	75.9	74.4
A	Control	1.23	0.123	3.8622	2.72	81.5	
A	Control	1.23	0.123	3.8622	2.417	65.8	
A	GTL Fuel 1,000 Hrs	1.23	0.123	3.8622	2.55	72.7	81.3
A		1.23	0.123	3.8622	2.93	92.4	
A		1.23	0.123	3.8622	2.666	78.7	
A	CARB Specification Diesel 500 Hrs→ GTL Fuel 500 Hrs	1.23	0.123	3.8622	2.611	75.9	82.3
A		1.23	0.123	3.8622	2.906	91.1	
A		1.23	0.123	3.8622	2.69	79.9	
A	CARB Specification Diesel 1,000 Hrs	1.23	0.123	3.8622	2.77	84.1	81.3
A		1.23	0.123	3.8622	2.837	87.6	
A		1.23	0.123	3.8622	2.542	72.3	
B	Control	0.91	0.139	2.8574	2.417	124.1	130.6
B	Control	0.91	0.139	2.8574	2.717	145.1	
B	Control	0.91	0.139	2.8574	2.393	122.4	
B	GTL Fuel 1,000 Hrs	0.91	0.139	2.8574	2.82	152.3	153.9
B		0.91	0.139	2.8574	2.852	154.6	
B		0.91	0.139	2.8574	2.857	154.9	
B	CARB Specification Diesel 500 Hrs→ GTL Fuel 500 Hrs	0.91	0.139	2.8574	2.723	145.5	143.6
B		0.91	0.139	2.8574	2.84	153.7	
B		0.91	0.139	2.8574	2.524	131.6	
B	CARB Specification Diesel 1,000 Hrs	0.91	0.139	2.8574	2.933	160.2	152.7
B		0.91	0.139	2.8574	2.816	152.0	
B		0.91	0.139	2.8574	2.726	145.7	
C1	Control	1.331	0.124	4.17934	3.88	123.2	110.6
C1	Control	1.331	0.124	4.17934	3.756	117.3	
C1	Control	1.331	0.124	4.17934	3.214	91.4	
C1	GTL Fuel 1,000 Hrs	1.331	0.124	4.17934	3.587	109.2	108.2
C1		1.331	0.124	4.17934	3.634	111.5	
C1		1.331	0.124	4.17934	3.473	103.8	
C1	CARB Specification Diesel 500 Hrs→ GTL Fuel 500 Hrs	1.331	0.124	4.17934	3.939	126.1	117.5
C1		1.331	0.124	4.17934	3.699	114.6	
C1		1.331	0.124	4.17934	3.64	111.8	
C1	CARB Specification Diesel 1,000 Hrs	1.331	0.124	4.17934	3.487	104.4	116.0
C1		1.331	0.124	4.17934	3.99	128.5	
C1		1.331	0.124	4.17934	3.71	115.1	

APPENDIX A-1.

Elastomer Compatibility Results (con't).

Elastomer Type	Condition	Inside Diameter	O-ring Thickness	Inside Circumference	Extension at Break	Elongation	Average Elongation
		(in)	*(in)*	*(in)*	*(in)*	*(%)*	*(%)*
C2	Control	1.35	0.103	4.239	3.824	117.5	143.3
C2	Control	1.35	0.103	4.239	4.666	157.2	
C2	Control	1.35	0.103	4.239	4.626	155.3	
C2	GTL Fuel 1,000 Hrs	1.35	0.103	4.239	4.403	144.8	147.8
C2		1.35	0.103	4.239	4.494	149.1	
C2		1.35	0.103	4.239	4.507	149.7	
C2	CARB Specification 500 Hrs→ GTL Fuel 500 Hrs	1.35	0.103	4.239	4.073	129.2	115.6
C2		1.35	0.103	4.239	3.757	114.3	
C2		1.35	0.103	4.239	3.523	103.3	
C2	CARB Specification Diesel 1,000 Hrs	1.35	0.103	4.239	5.657	203.9	170.1
C2		1.35	0.103	4.239	4.506	149.6	
C2		1.35	0.103	4.239	4.656	156.7	

APPENDIX A-2.

Detailed Chassis Emissions Results from Yosemite Waters Testing, Ordered by Run Number.

Run	Vehicle	Fuel	Emission Control	Cycle	CO	NO_x 1	NO_x 2	NO	HC	PM	CO_2	MPG
2792-1	201	CARB	None	NYCB	5.09	31.9	31.6		1.56	0.61	3890	2.57
2792-2	201	CARB	None	NYCB	5.52	32.3		28.3	1.37	0.55	3856	2.69
2792-3	201	CARB	None	NYCB	6.18	30.7		27.5	1.54	0.56	3940	2.54
				Average	**5.60**	**31.6**		**27.9**	**1.49**	**0.57**	**3895**	**2.60**
2793-1	201	CARB	None	CSHVR	2.00	11.5	11.8		0.42	0.19	1461	6.86
2793-2	201	CARB	None	CSHVR	1.91	11.6		10.3	0.48	0.19	1455	6.88
2793-3	201	CARB	None	CSHVR	1.89	11.1		10.0	0.45	0.17	1414	7.09
				Average	**1.93**	**11.4**		**10.2**	**0.45**	**0.18**	**1443**	**6.94**
2797-1	202	CARB	None	NYCB	6.26	33.3	33.9		1.48	0.67	3932	2.55
2797-2	202	CARB	None	NYCB	6.92	34.5		31.3	1.34	0.63	4073	2.46
2797-3	202	CARB	None	NYCB	9.35	32.3		28.4	1.33	0.80	3857	2.59
				Average	**7.51**	**33.4**		**29.9**	**1.38**	**0.70**	**3954**	**2.53**
2798-1	202	CARB	None	CSHVR	1.90	11.9	12.3		0.45	0.17	1417	7.07
2798-2	202	CARB	None	CSHVR	2.15	11.6		10.5	0.52	0.17	1396	7.17
2798-3	202	CARB	None	CSHVR	2.80	11.6		10.7	0.47	0.16	1403	7.14
				Average	**2.28**	**11.7**		**10.6**	**0.48**	**0.17**	**1405**	**7.13**
2802-1	203	CARB	None	NYCB	4.68	32.1	32.2		1.56	0.80	3988	2.51
2802-2	203	CARB	None	NYCB	5.41	31.9		28.6	1.87	0.65	3997	2.50
2802-3	203	CARB	None	NYCB	6.25	32.0		29.1	1.84	0.65	4072	2.46
				Average	**5.45**	**32.0**		**28.9**	**1.76**	**0.70**	**4019**	**2.49**
2805-1	203	CARB	None	CSHVR	1.39	12.1	12.1		0.43	0.16	1476	6.79
2805-2	203	CARB	None	CSHVR	1.36	11.7		10.6	0.47	0.15	1422	7.05
2805-3	203	CARB	None	CSHVR	1.53	11.6		10.7	0.43	0.15	1408	7.12
				Average	**1.43**	**11.8**		**10.7**	**0.44**	**0.15**	**1435**	**6.99**
2809-1	205	GTL	CCRT	NYCB	0.00	25.9	25.6		0.00	0.05	3609	2.56
2809-2	205	GTL	CCRT	NYCB	0.00	25.7		13.2	0.00	0.02	3595	2.57
2809-3	205	GTL	CCRT	NYCB	0.00	24.8		13.7	0.00	0.02	3520	2.62
				Average	**0.00**	**25.5**		**13.5**	**0.00**	**0.03**	**3575**	**2.58**
2813-1	205	GTL	CCRT	CSHVR	0.00	9.1	9.1		0.00	0.00	1268	7.29
2813-2	205	GTL	CCRT	CSHVR	0.00	8.7		4.2	0.00	0.00	1224	7.55
2813-3	205	GTL	CCRT	CSHVR	0.00	8.7		4.3	0.00	0.00	1220	7.57
				Average	**0.00**	**8.8**		**4.3**	**0.00**	**0.00**	**1237**	**7.47**
2819-1	205	GTL	None	NYCB	5.56	26.6	26.5		0.28	0.37	3479	2.65
2819-2	205	GTL	None	NYCB	4.91	26.3		23.9	0.36	0.36	3494	2.64
2819-3	205	GTL	None	NYCB	5.33	26.8		24.9	0.42	0.30	3588	2.57
				Average	**5.27**	**26.6**		**24.4**	**0.35**	**0.34**	**3187**	**2.62**
2820-1	205	GTL	None	CSHVR	1.26	9.5	9.7		0.16	0.10	1248	7.38
2820-2	205	GTL	None	CSHVR	1.27	9.2		8.5	0.15	0.08	1208	7.63
2820-3	205	GTL	None	CSHVR	1.32	9.2		8.6	0.14	0.09	1218	7.57
				Average	**1.28**	**9.3**		**8.6**	**0.15**	**0.09**	**1225**	**7.53**

APPENDIX A-2.

Detailed Chassis Emissions Results from Yosemite Waters Testing, Ordered by Run Number (con't).

Run	Vehicle	Fuel	Emission Control	Cycle	CO	NO_x 1	NO_x 2	NO	HC	PM	CO_2	MPG
2822-1	206	GTL	CCRT	CSHVR	0.00	10.6	10.5		0.00	0.00	1409	6.56
2822-2	206	GTL	CCRT	CSHVR	0.00	10.3		4.5	0.00	0.00	1371	6.74
2822-3	206	GTL	CCRT	CSHVR	0.00	10.5		4.4	0.00	0.00	1369	6.75
				Average	**0.00**	**10.5**		**4.5**	**0.00**	**0.00**	**1383**	**6.68**
2823-1	206	GTL	CCRT	NYCB	0.00	25.8	26.1		0.00	0.01	3388	2.73
2823-2	206	GTL	CCRT	NYCB	0.00	27.8		14.4	0.00	0.00	3593	2.57
2823-3	206	GTL	CCRT	NYCB	0.00	27.4		15.2	0.00	0.06	3516	2.63
				Average	**0.00**	**27.0**		**14.8**	**0.00**	**0.02**	**3499**	**2.64**
2826-1	206	GTL	None	NYCB	4.58	27.8	27.3		0.33	0.48	3572	2.58
2826-2	206	GTL	None	NYCB	5.59	29.0		27.5	0.54	0.46	3701	2.49
2826-3	206	GTL	None	NYCB	4.89	29.8		28.2	0.54	0.40	3856	2.39
				Average	**5.02**	**28.9**		**27.9**	**0.47**	**0.45**	**3710**	**2.49**
2828-1	206	GTL	None	CSHVR	1.55	11.6	11.3		0.15	0.11	1369	6.73
2828-2	206	GTL	None	CSHVR	1.39	11.6		11.2	0.20	0.10	1375	6.70
2828-3	206	GTL	None	CSHVR	1.45	11.2		10.9	0.21	0.09	1353	6.81
				Average	**1.46**	**11.5**		**11.1**	**0.19**	**0.10**	**1366**	**6.75**
2830-1	204	GTL	CCRT	CSHVR	0.00	10.8	11.6		0.00	0.00	1364	6.77
2830-2	204	GTL	CCRT	CSHVR	0.08	10.8		4.9	0.00	0.00	1321	6.97
2830-3	204	GTL	CCRT	CSHVR	0.00	10.7		5.3	0.00	0.00	1321	6.99
				Average	**0.03**	**10.8**		**5.1**	**0.00**	**0.00**	**1335**	**6.91**
2833-1	204	GTL	CCRT	NYCB	0.00	28.2	27.0		0.00	0.01	3229	2.62
2833-2	204	GTL	CCRT	NYCB	0.00	28.6		12.7	0.00	0.01	3615	2.56
2833-3	204	GTL	CCRT	NYCB	0.00	27.1		11.8	0.00	0.00	3535	2.61
				Average	**0.00**	**28.0**		**12.3**	**0.00**	**0.01**	**3460**	**2.60**
2835-1	204	GTL	None	NYCB	7.55	28.3	18.9		0.55	0.92	3650	2.52
2835-2	204	GTL	None	NYCB	8.76	29.4		26.5	0.65	0.63	3617	2.54
2835-3	204	GTL	None	NYCB	8.94	28.0		26.7	0.63	0.61	3561	2.58
				Average	**8.42**	**28.6**		**26.6**	**0.61**	**0.72**	**3276**	**2.55**
2837-2	204	GTL	None	CSHVR	2.33	11.1		11.0	0.24	0.16	1341	6.86
2837-3	204	GTL	None	CSHVR	2.11	10.9		11.3	0.24	0.15	1318	6.98
2837-4	204	GTL	None	CSHVR	2.45	11.2	11.2		0.24	0.14	1312	7.01
				Average	**2.30**	**11.1**		**11.3**	**0.24**	**0.15**	**1324**	**6.95**

APPENDIX A-3.

Description of Statistical Technique Used to Analyze Emissions Results for Statistical Significance.

The statistical analysis of the emissions data is performed using a mixed-model analysis of variance (ANOVA) approach. The model accounts for the fixed effects of test fleet (CARB/none, GTL/none, and GTL/CCRT) and test cycle (CSHVR and NYCB) and the random effects of differences in vehicles, tests, and measurements. Specifically, the full model used for the analyses is

$$Y_{ijklr} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \gamma_{k(j)} + \delta_{l(j)} + \varepsilon_{r(ijkl)},$$

where Y_{ijklr} denotes the r^{th} replicate measurement in the l^{th} test run on the k^{th} vehicle under cycle j for fleet i. The terms α_i and β_j denote the fixed effects of fleet and cycle, respectively, while the term $\alpha\beta_{ij}$ denotes the interaction of fleet and cycle. This term allows the effect of fleet to vary by cycle. The random effect $\gamma_{k(j)}$ accounts for vehicle-to-vehicle variability, while the random effect $\delta_{l(j)}$ explains the test-to-test variability. The error term $\varepsilon_{r(ijkl)}$ represents the variability of the three replicate measurements made within a specific test run. The subscript *r(ijkl)* refers to nesting of replicate numbers within unique test runs. It is assumed that the random effects are independent and distributed approximately by a normal (Gaussian) distribution with mean zero and standard deviations $\sigma_{\gamma j}$, $\sigma_{\delta j}$, and $\sigma_{\varepsilon j}$, respectively. The index j indicates that the standard deviations of the effects $\gamma_{k(j)}$, $\delta_{l(j)}$, and $\varepsilon_{r(ijkl)}$ are estimated separately by cycle. This model was applied separately for each pollutant using the PROC MIXED procedure in the Statistical Analysis System (SAS®) software. Comparisons between fleet by cycle and between cycle by fleet were obtained using the DIFF=ALL option on the LSMEANS statement. Ninety-five percent (95%) confidence intervals were calculated for the estimated means and differences. Satterthwaite's method was used to determine the degrees of freedom associated with the standard errors of the estimates.

The exceptions to the approach described above are as follows: For the pollutants CO, HC, and PM, the GTL/CCRT results are too small to include in the full model. Thus, the model for these pollutants includes only the unfiltered results. Because the effects of vehicle and test are confounded in the remaining data, it is not possible to separate the vehicle-to-vehicle variability from the test-to-test variability. Thus, the vehicle-to-vehicle variance component is removed from the model, and the remaining "test-to-test" variance component represents both test-to-test and vehicle-to-vehicle variability. Comparisons between the unfiltered results are performed in the same manner as they are for the other pollutants. However, because the mean and standard error for the filtered results are essentially zero, we compare the means of the remaining two fleets to the mean for the filtered fleet by testing whether the CARB/none and GTL/none means are zero. We do this by constructing a *t*-statistic using the means and standard errors estimated by the model for these two fleets. The other exception to this approach involves the comparisons between the filtered and unfiltered results for PM under the NYCB cycle. In this case there are a few non-zero results for PM, though these results are still too small to include in a model. To compare GTL/CCRT with the other two fleets for NYCB PM, we use a two-sample *t*-test using the modeled mean and standard error for the CARB/None or GTL/None fleet and the sample mean and standard error for the GTL/CCRT fleet.