Yosemite Waters

Vehicle Evaluation Report

Final Results

Prepared for South Coast Air Quality Management District
by the National Renewable Energy Laboratory

CRD-01-098
Fischer-Tropsch Synthetic Fuel Demonstration in a Southern California Vehicle Fleet

YOSEMITE WATERS VEHICLE EVALUATION REPORT

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August 2005

Acknowledgements

This evaluation of Yosemite Waters would not have been possible without the support and cooperation of many people. The authors wish to acknowledge the following participants.

South Coast Air Quality Management District
Adewale Oshinuga
Matt Miyasato

Yosemite Waters
Ron Lansing

International Truck and Engine Corporation
Tom Corcoran

Johnson Matthey
Sougato Chatterjee
Todd Jacobs

Shell Global Solutions (US) Inc.
Ralph Cherrillo
Ian Virrels

West Virginia University
Nigel Clark
W. Scott Wayne

Westrux
Team of mechanics

This report is available from the Alternative Fuels Data Center at www.eere.energy.gov/afdc/resources/doc_database.html.

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Table of Contents

Executive Summary

Overview

In 1992, Congress enacted the Energy Policy Act (EPAct) to enhance energy security in the United States and improve air quality. The regulation requires certain fleets to use alternative transportation fuels to reduce petroleum consumption and decrease the nation's dependence on foreign oil. The law, as passed, included a list of specific fuels that met the following requirements:

- Are substantially non-petroleum,
- Yield substantial energy security benefits, and
- Offer substantial environmental benefits.

EPAct authorizes the U.S. Department of Energy (DOE) to add to the list of EPAct-authorized alternative fuels through a petition process. To be considered by DOE, petitioners must show that their fuels meet the previously mentioned criteria. Beginning in late 1999, three companies petitioned DOE to consider adding synthetic diesel fuels to the list of EPAct-authorized alternative fuels. These fuels were created using a "gas-to-liquids" (GTL) process.

Gas-to-liquid fuels, also called Fischer-Tropsch diesel fuels (FTD), are made from natural gas using a Fischer-Tropsch process. Because natural gas (the feedstock) is not petroleum, it meets the first EPAct fuel requirement. According to the *Status Review of DOE Evaluation of FTD Fuel as a Candidate Alternative Fuel*, the two remaining substantial benefits requirements are as of yet undefined.[1] More information was needed to show that the fuel meets these two requirements.

Regardless of the status of the petitions to DOE, FTD or GTL fuel is increasing in use throughout the world. Fleet trials are being conducted both in the United States and abroad.[2] This study discusses the results of one of these fleet trials.

This study was a joint effort between the South Coast Air Quality Management District (SCAQMD) and the National Renewable Energy Laboratory (NREL). The overall goal of the project was to evaluate the use of GTL fuel in combination with passive catalytic regenerative particle filters in real-world service and characterize regulated and unregulated exhaust pollutant emissions from GTL fuel in comparison to petroleum-derived diesel fuel.

The joint project included several tasks to accomplish the objectives:

- Fuel/engine compatibility testing: Conduct laboratory tests to describe the chemical, physical, and operability characteristics of the fuel. The purpose was to identify potential material compatibility issues with using GTL fuel in the study vehicles.
- Vehicle retrofits: Design and install emissions control devices on test vehicles.
- Emissions testing: Conduct two rounds of emissions tests on the study vehicles over various duty cycles to measure the emission reductions from using GTL fuel with an emission control device.
- Fleet operability: Collect data on the vehicles in service to determine the differences between performance of the study vehicles and a set of nominally identical baseline vehicles.

The focus of this document is the fleet operability task. Although the results from the other tasks will be briefly summarized, details of each were the subject of several Society of Automotive Engineers (SAE) papers. For more details on those results, see the References section.

DOE/NREL and Partners

SCAQMD is the air pollution control agency for the four-county region in Southern California (Los Angeles, Orange, and parts of

Riverside and San Bernardino). In addition to controlling emissions from stationary sources of air pollution, SCAQMD works on transportation-related programs that promote cleaner fuels and vehicles.

NREL is DOE's premier laboratory for renewable energy and energy efficiency research, development, and deployment. NREL's Center for Transportation Technologies and Systems is involved in projects investigating vehicle technologies that will reduce U.S. dependence on foreign petroleum without increasing emissions.

In early 2000, SCAQMD and NREL entered into a Cooperative Research and Development Agreement to address GTL as a transportation fuel. Several partners joined the project. The partners and their respective roles are listed below.

SCAQMD: Co-funded the project and was responsible for project planning and oversight.

NREL: Co-funded the project and acted as project technical monitor with a goal to facilitate alternative fuel and technology market penetration through reduction of technical barriers.

Shell Global Solutions (US) Inc.: Provided its GTL Fuel for the study vehicles and led in permitting and installing the temporary tank for the fleet.

Yosemite Waters' Fullerton Bottling Plant is the company's corporate headquarters.

NREL/PIX 14081

Yosemite Waters: Operated the study vehicles in daily service, fueled the study vehicles with Shell's GTL Fuel, shared operations and fueling data with NREL.

International Truck and Engine Corporation: Manufactured the study vehicles and ensured the vehicle engines worked properly.

Johnson Matthey (JM): Designed and manufactured the emission control device used in the study.

Westrux: Installed the emission control devices at the beginning of the project, performed maintenance and warranty work during the study, and returned the vehicles to their original configuration at the end of the demonstration.

West Virginia University: Performed emissions tests using its transportable chassis dynamometer.

Host Site Description

The host site for this evaluation was the Fullerton Bottling Plant, which is also the corporate headquarters for Yosemite Waters. Yosemite Waters has been delivering bottled water to commercial and residential customers in Southern California for the last 70 years. The company operates from four bottling plants and five district warehouses in Southern California. Yosemite Waters' core business is delivery of 5 gal water bottles and dispenser systems for residential and commercial customers.

The Yosemite Waters fleet was considered for the project for two main reasons. The Fullerton location is within the boundaries of SCAQMD and the fleet had recently purchased six identical International Class 6 trucks. When approached with the project, the fleet was eager to participate.

Vehicle and Equipment Descriptions

The six trucks used in the study were of identical configuration (see Table 1) and manufactured by International Truck and Engine Corporation. The study vehicles featured International's latest technology engine.

Three of the vehicles were designated as "baseline" vehicles. No modifications were made to these vehicles, which were fueled with standard California Air Resources Board (CARB) specification diesel fuel. The remaining three "test" vehicles were fitted with JM Catalyzed Continuously Regenerating Technology (CCRT®) particle filters and fueled with Shell's GTL Fuel during the study period. The CCRT filter is a diesel oxidation catalyst followed by a wall-flow catalyzed soot filter.

Each Yosemite Waters vehicle operated on a dedicated 10-day route with varying amounts of city and highway driving. Therefore, each vehicle had a unique drive cycle, and the selection of each group of vehicles required careful consideration. Table 2 presents route and duty-cycle characteristics for each individual vehicle and indicates the group selection for each.

One factor in selecting the vehicles for each group was the percentage of highway miles. As shown in Table 2, vehicles 201 and 204 had the lowest percentage of highway miles. Evaluating these two trucks in the same group could bias the real-world fuel economy, as lower fuel economy is recorded during city driving. Because of this, vehicles 201 and 204 were assigned to the baseline and test groups, respectively. The other vehicles exhibited similar percentages of highway miles and were divided so consecutive vehicle numbers were in the same category (201, 202, and 203 were baseline).

To ensure that no residual CARB specification diesel fuel was in the fuel systems, the test vehicles operated on Shell's GTL Fuel for approximately two weeks prior to installing the emission control devices. Testing has shown that the CCRT filter has good low-temperature performance—an important characteristic in selecting the filter for this project.[3] 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

NREL/PIX 14082

Figure 1. Yosemite Waters truck by International Truck and Engine Corporation

Table 1. Vehicle Specifications

Feature	Description
Chassis Manufacturer/Model	International/4300
Chassis Model Year	2001
Engine Manufacturer/Model	International/DT466
Emission Certification Year	2000
Engine Ratings - Max. hp - Max. torque	 195 hp @ 2,300 rpm 520 ft-lb
Engine Configuration	Inline six cylinder
Fuel System Storage Capacity	55 gal
Transmission Manufacturer/Model	Allison 2000
Gross Vehicle Weight	26,000 lb
Particulate Filter	Johnson Matthey CCRT®

Table 2. Drive-cycle Characteristics for Each Truck

Vehicle Number	Group	Fuel/Emission Control Device	Total Miles	% Hwy. Miles
201	Baseline	CARB diesel/none	532	36
202			752	75
203			1030	75
204	Test	GTL Fuel/CCRT filter	680	61
205			667	82
206			837	77

What Is a CCRT Filter?

The CCRT filter is Johnson Matthey's second-generation heavy-duty diesel retrofit system optimized for more challenging applications. The patented CCRT filter's advanced catalyst optimization requires no supplemental heat source and is verified to reduce hydrocarbons (HC), carbon monoxide (CO), and particulate matter (PM) by more than 90% in 1994 and newer engines with exhaust temperatures averaging as low as 210°C. Based on JM's patented CRT® two-stage filter technology, CCRT filters use two distinct catalytic formulas specifically engineered for each application. Upstream, a JM oxidation catalyst coated on a flow-through substrate (or DOC) reduces HC and CO and optimizes conditions for the second, downstream catalytically-coated, wall-flow filter to burn off virtually all of the PM.
Source: www.jcmcataylsts.com

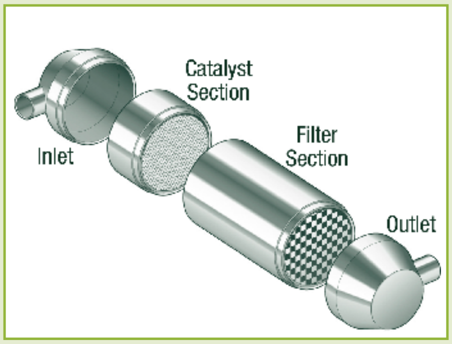

Table 3. Measured Fuel Properties for Shell's GTL Fuel

Property	Test Method	GTL Results	CARB Specification Results
Density, g/mL	ASTM D4052	0.7838	0.8312
Viscosity, mm^2/sec at 40ºC	ASTM D445	3.468	2.539
Flash Point, ºC	ASTM D93	89	70
Sulfur, ppm	ASTM D5453	0.5	70.5
Carbon to Hydrogen Ratio		2.13	~1.8
Aromatics, Percentage by Mass	ASTM D5186		
Monoaromatics		1.4	10.7
Polynuclear Aromatics		<0.1	1.4
Total Aromatics		1.4	12.1
Heat of Combustion, BTU/lb	ASTM D240		
Gross		20,246	18,145
Net		18,878	16,878
Cetane Number	ASTM D613	79.5	56
Distillation, ºC	ASTM D86		
Initial Boiling Point		209	183
50%		299	252
90%		331	315
Final Boiling Point		343	346
Cloud Point, ºC	ASTM D2500	1	-15
Pour Point, ºC	ASTM D97	-6	-27
Water and Sediment	ASTM D1796	<0.02	0.01
Copper Corrosion	ASTM D130	1A	1A
Ash, Percentage by Mass	ASTM D482	<0.001	<0.001
Carbon Residue, Percentage by Mass	ASTM D524	0.03	0.06
High Frequency Reciprocating Rig, Wear Scar, mm	ASTM D6079	0.395	0.590

acceptable. Exhaust pressure and temperature histograms collected over several months showed stable filter operation. After these data were analyzed, vehicles 205 and 206 were retrofit as well. A more detailed description of the monitoring results was published in an SAE paper in fall 2004.[4]

Fuel Properties and Test Results

Fischer-Tropsch is a process by which natural gas, coal, or other feedstock is converted to a clean-burning liquid fuel that can be substituted for or blended with diesel fuel. In contrast to conventional diesel fuels, Fischer-Tropsch diesel is virtually sulfur and aromatic free and has a very high cetane number. Fuel produced through the Fischer-Tropsch process has been used as a neat fuel in South Africa and as a blend stock in traditional diesel fuels to meet the California diesel quality standards. These fuels can be operated in heavy-duty diesel vehicles without any modifications to the engine or fuel system.[4]

Much of the literature describing previous work with GTL did not provide complete fuel properties.[5] As part of this study, an analysis of the properties of Shell's GTL Fuel was performed. The detailed fuel properties were published in the 2004 SAE paper.[4] A summary of Shell's GTL Fuel properties is featured in Table 3. The table includes CARB specification diesel fuel properties for reference.

In addition to the physical, chemical, and operational properties, the impact of GTL fuel on the fuel injection equipment was examined. When changing between fuels with different properties, elastomeric components may suffer. In this study, the Yosemite Waters vehicles were changed from a nominally 15% aromatic CARB specification diesel fuel to a near zero aromatic GTL fuel. This change in aromatic content may cause reduced swelling in elastomers, such as o-rings, in the fuel injection equipment.[6] To determine if this might occur, bench studies were carried out with new elastomers from the International DT466 engines used in the study. The results from these exposure studies showed similar behavior for the elastomers in CARB specification diesel and Shell's GTL Fuel.

Prior to the switch to Shell's GTL Fuel, no preventative maintenance, such as replacing elastomers in the fuel injection equipment, was performed on the vehicles. The vehicles were switched overnight from one fuel to the other.

Project Design and Data Collection

The goals of the fleet operability task were to evaluate the use of Shell's GTL Fuel in combination with passive catalytic regenerative particle filters in real-world service and to characterize performance differences from vehicles operating on conventional diesel fuel. The data collection process followed a proven protocol developed by NREL for DOE heavy-vehicle evaluation projects. As outlined in the *General Evaluation Plan: Fleet Test and Evaluation Projects*,[7] this protocol has been used for various projects, including evaluation of vehicles using alternative fuels (compressed natural gas, liquefied natural gas, biodiesel) and electric propulsion systems (hybrid electric and fuel cell).

The data collection process included records from all six vehicles: three test vehicles operating on Shell's GTL Fuel with CCRT filters and three identical, unmodified vehicles operating on CARB specification diesel fuel. Data were collected from the fleet during the study period and included electronic and paper records. Data parameters included:

- Diesel fuel consumption by vehicle
- Shell's GTL Fuel consumption by vehicle
- Mileage data from every vehicle
- Preventative maintenance actions, such as oil and filter changes
- Unscheduled maintenance actions

The data collection was designed to cause as little disruption to the fleet as possible. Electronic records were sent by e-mail and paper records were mailed to NREL. Project partners visited the fleet on several occasions to gather impressions on the project and fuel use.


NREL/PIX 14083

Figure 2. Maintenance building at the Fullerton Bottling Plant

NREL/PIX 14084

Figure 3. Temporary GTL fueling tank

Facilities and Fueling Storage

The Fullerton Bottling Plant is also headquarters for Yosemite Waters. The plant houses staff offices and purification and bottling equipment. A small maintenance building at the rear of the property allows for routine maintenance and inspections of the vehicles by on-site staff. During the project, the local International dealer, Westrux, handled major repairs and warranty work on the trucks.

Project Startup

The six International trucks were delivered to the Yosemite Waters fleet in late 2001 and placed in service in January 2002. The fleet fuels its vehicles with CARB specification diesel fuel at a local station. Once the fleet agreed to participate in the demonstration, Shell began the process of getting the local permits required to install a temporary fuel tank on site. During the test period, Shell supplied its GTL Fuel to the temporary tank as needed.

The fueling tank installation was completed in November 2002. As previously mentioned, vehicle 204 was selected for the first CCRT filter installation to make sure the temperature and back pressure for the engine was sufficient for correct operation. The vehicle ran on Shell's GTL Fuel for two weeks prior to CCRT filter installation to ensure all CARB specification diesel fuel was flushed from the system. Vehicle 204 went back into service in mid-January 2003 and was monitored closely for several months. Once the project partners were satisfied the CCRT filter operated properly in combination with the truck, an order was placed for the remaining two filters. Because of contracting issues, the remaining filters were not completed and delivered until late that year.

NREL/PIX 14078

A Yosemite Waters employee operates a company bottling system.

NREL/PIX 14085

Figure 4. Low clearance of the CCRT resulted in damage

During that time, vehicles 205 and 206 operated on Shell's GTL Fuel without the filters. In early December 2004, the filters were installed and the test period began.

The original vehicles in this study came equipped with a factory muffler located under the cabs. The CCRT filters were designed to replace this muffler for the three test vehicles. Westrux conducted the retrofit on each vehicle. During installation of the first filter, Westrux found evidence that the factory muffler occasionally scraped the ground during normal operation. Therefore, the CCRT filter was moved above the drop frame to eliminate potential damage.

Despite this adjustment, the fleet experienced problems with low clearance. Yosemite Waters' deliveries to residential and commercial customers require the drivers to enter driveways and traverse speed bumps. Although the filters were not disabled, the driving conditions did cause damage (see Figure 4).

To assess their performance, the CCRT filters were equipped with data loggers. The data loggers collected exhaust temperature and back pressure information. At the end of the project, the data loggers were removed from the vehicles (along with the filters) and shipped to JM. During transit, the data logger from vehicle 205 was damaged, and the data were lost.

Figure 5 shows the exhaust temperature profile collected for vehicle 204. The figure illustrates the low average exhaust temperature of this vehicle, which was greater than 210°C for 40% of the total operating time. The peak back pressure for vehicle 204 is shown in Figure 6. The stable exhaust back pressure over this project indicates that even in relatively low temperatures, the CCRT filter continued to operate effectively.

As evident in Table 2 (see page 3), the average highway miles for vehicle 206 were greater than vehicle 204. This resulted in a higher average exhaust temperature of 240°C for 40% of the operating time (see Figures 5 and 7). The back pressure from vehicle 206 was similar to that of vehicle 204—steady throughout the study period (see Figures 6 and 8).

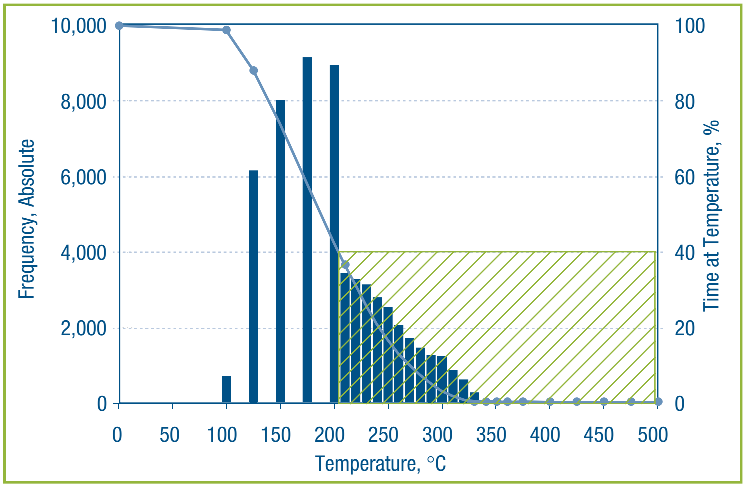

Figure 5. Exhaust temperature profile for vehicle 204

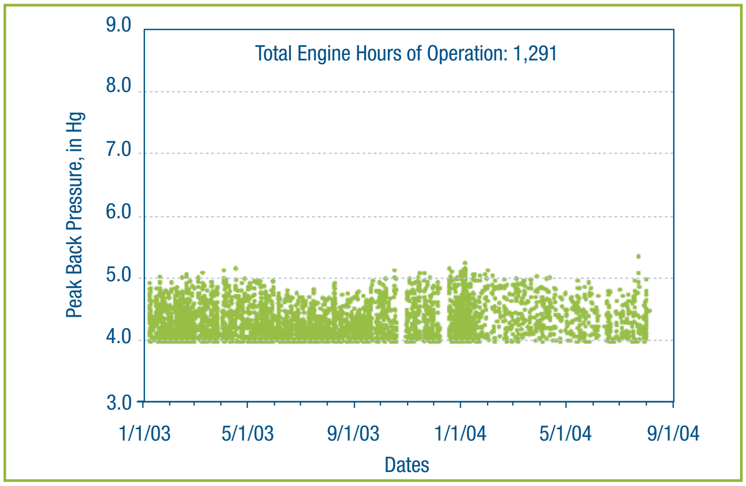

Figure 6. Exhaust back pressure for vehicle 204

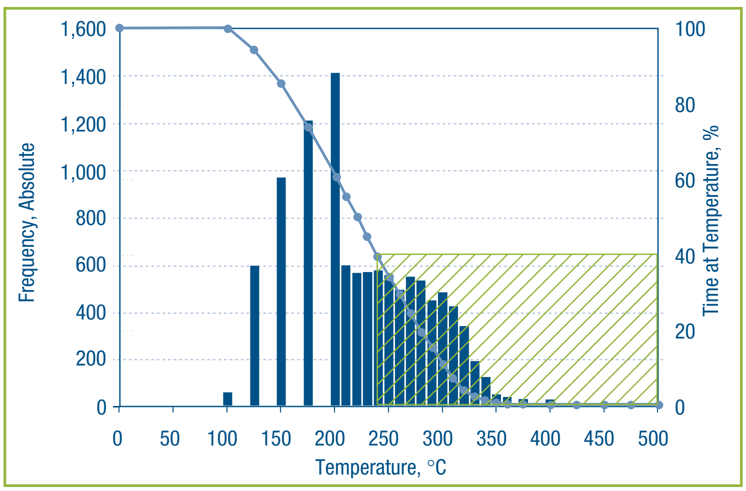

Figure 7. Exhaust temperature profile for vehicle 206

Evaluation Results

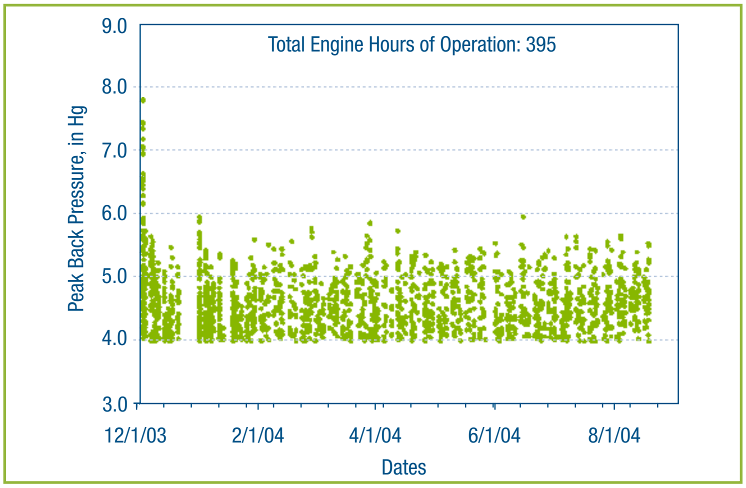

Figure 8. Exhaust back pressure for vehicle 206

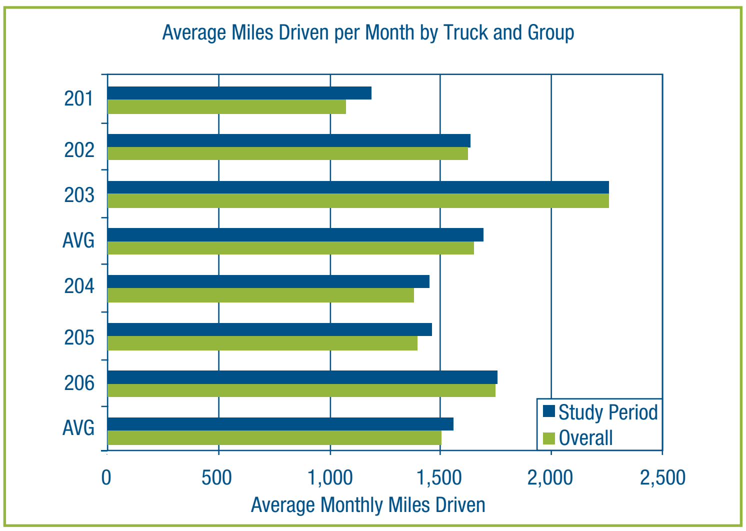

Figure 9. Average miles driven per month by vehicle and group

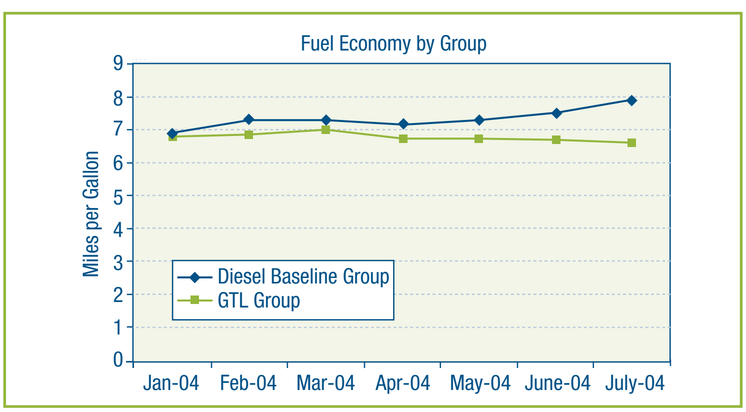

Figure 10. Monthly average fuel economy by fuel group

Truck Use and Duty Cycle

As previously mentioned, the study vehicles operated out of the Fullerton Bottling Plant, and each truck operated on a dedicated 10-day route with varying degrees of city and freeway driving. The vehicles had assigned drivers responsible for sales and marketing and the delivery of bottled water on their specified routes. The trucks left the plant early each weekday, traveled primarily by highway to the route start, then drove urban stop-and-go during the delivery period.

Throughout the evaluation, the trucks performed the required service for the fleet. Figure 9 shows the average monthly miles by truck and group during the study period. It also shows the average monthly miles driven over the life of the vehicle. Additionally, the figure illustrates the variability between trucks because of the specific duty cycles.

Fuel Economy

During the study period, fuel economy data were collected using fueling volumes and hub odometer readings. Average fuel economy values were calculated for each truck, as well as for the baseline and test groups. Monthly fuel economy values during the study period for the diesel control and GTL-fueled group are presented in Figure 10. Average fuel economy values are presented in Table 4.

Results indicate that the average fuel economy during the diesel-fueled group study period exceeded that of the GTL-fueled group by approximately 8%. However, based on statistical analysis conducted on the mean group fuel economy values, there is no statistical difference between the mean group fuel economy values.

Overall Maintenance Costs

Maintenance expenses accrued by the trucks in this evaluation were attributed to labor charges by maintenance staff and the cost of replacement parts. (For comparison purposes, a labor charge of $50 per hour is used in the cost calculations.) Maintenance events are described in Table 5.

As noted in Table 5, labor and parts costs attributed to warranty events are unknown and represent a zero cost assessed to the fleet. Warranty costs are included as a part of the purchase agreements with a vehicle manufacturer. Operator-reported defects and scheduled preventative maintenance events did have costs associated with labor and parts and were reported for each vehicle. These events were also summarized for comparison between the diesel baseline group and GTL-fueled group.

During the test period (January 2004 through July 2004), maintenance costs for operator-reported defects and preventative maintenance events were compiled.

Results show that the GTL-fueled group had a cost per mile nearly twice that of its diesel counterpart. However, it is important to note that vehicle 206 is the primary cause of the high cost per mile within the GTL-fueled group. Maintenance data reveal two expensive labor events to replace the starter in vehicle 206. This cost $961. No other vehicle in the evaluation exhibited starter problems, and the starter was not expected to be impacted by GTL fuel. If the $961 is removed from consideration, the cost per mile comparison between the two groups is much closer and comparable, as presented in Table 6.

Maintenance Costs by Vehicle Subsystem

It is often useful to compare maintenance costs specific to vehicle subsystems that may be impacted by different fuels. Comparison of maintenance costs in total or for ancillary systems is of interest but does not provide the insight and relevancy of comparison of vehicle subsystems that may be impacted by a fuel change. The engine and fuel system are the two subsystems that may be affected differently by the change to GTL fuel, and therefore the maintenance costs attributed to these subsystems were evaluated.

Evaluation of maintenance events related to these two subsystems reveals that only four relevant events occurred during the test

Table 4. Average Fuel Economy Values for Study Period

Truck/Group	Fuel Economy (mpg)*
201	6.6
202	7.7
203	7.5
Diesel Average	**7.3**
204	6.2
205	7.0
206	7.2
GTL Average	**6.8**

* Calculations were performed using appropriate significant digits, and table values were rounded for display purposes.

Table 5. Fleet Maintenance Categories

Maintenance Category	Description
Warranty	Warranty events are filed by the fleet but do not involve direct costs to the fleet (including labor charges or parts costs).
Operator-Reported Defect	Mechanical defects noted by the operator and reported to maintenance. These are not warranty items and incur labor and parts costs.
Preventative Maintenance	Regularly scheduled events, which include oil and oil filter changes, and fuel filter and air filter replacements.

Table 6. Adjusted Maintenance Cost Summary

Vehicle	Fuel	Maintenance Cost	Miles Driven	Cost/Mile
201	Diesel	$ 189	8,290	$ 0.023
202	Diesel	$ 237	11,411	$ 0.021
203	Diesel	$ 474	15,813	$ 0.030
204	GTL	$ 189	10,129	$ 0.019
205	GTL	$ 189	10,215	$ 0.019
206	GTL	$ 237	12,310	$ 0.019 *
Diesel Group		$ 900	35,514	$ 0.025
GTL Group		$ 615	32,654	$ 0.019

* Omitting $961 for starter replacement (failure unrelated to fuel)

period. All four were warranty events and did not incur costs to the fleet. As previously noted, true costs of warranty events are not known. Therefore, as presented in Table 7, there is no measurable difference in maintenance costs for the engine and fuel system in either fuel group.

Cost Comparisons

"The price of Shell's GTL Fuel is likely to be related to the price of conventional diesel fuel and will depend on a number of factors such as global market demand and the level of taxation. As the tax element is a significant proportion of the end price, the price of Shell's GTL Fuel to the consumer depends on the level of taxation decided upon. With limited volumes of Shell's GTL Fuel available until the end of the decade, the cost of delivering Shell's GTL Fuel to California is likely to be slightly higher than normal refinery diesel fuel. GTL plants are economically viable where there are large gas reserves, stable fiscal environments and favorable construction costs - which are present in a number of Middle East locations including Qatar." *Source: Shell Global Solutions (US) Inc.*

Table 7. Fuel System and Engine Maintenance Costs

Vehicle	Fuel	Fuel System or Engine Maintenance Event	Warranty
201	Diesel	Repaired leaking oil pump	Yes
203	Diesel	Replaced leaking oil pump	Yes
206	GTL	Repaired fuel leak, leaking oil pump	Yes

Overall Operating Costs

Generally, total operating costs are the sum of fuel and maintenance costs per mile. These values allow a cost comparison between the baseline and test groups. The price of Shell's GTL Fuel is not reported in this document under agreement with Shell Global Solutions (US) Inc., the fuel provider (see Cost Comparisons).

In the absence of Shell's GTL Fuel costs, diesel costs are not reported in this document. An overall operating cost comparison is therefore incomplete and consists of the maintenance cost comparison in the previous section.

Emission Test Results

West Virginia University (WVU) collected chassis exhaust emissions for the six study vehicles. WVU's Transportable Vehicle Emissions Testing Laboratories gather emissions data from in-use heavy-duty vehicles. Detailed information pertaining to the design and operation of the laboratories has been previously published.[8-10]

Testing was conducted over two different test cycles—the City Suburban Heavy Vehicle Route (CSHVR) and the New York City Bus (NYCB) cycle. These cycles were selected to simulate the higher-speed arterial driving and the lower-speed, stop-and-go residential driving that the Yosemite Waters vehicles do in the real world. Schematics of the cycles are illustrated in Figures 12 and 13.

Two rounds of emission testing were performed during the study. The first round of emissions was collected in December 2003–the beginning of the operability period. The second round of emissions was collected in July 2004, the end of the period. The baseline vehicles were tested "as is" with no modifications. The test vehicles were tested with Shell's GTL Fuel with and without the CCRT filters. By removing the filters, the impact of the fuel on emissions could be isolated from the combined fuel and filter effect.

Figure 14 illustrates the emissions over the CSHVR cycle. Shell's GTL Fuel (no filter) reduced the emissions compared to the CARB specification diesel fuel in both rounds of testing. Further emission reductions were possible with the CCRT filter and Shell's GTL Fuel.

Emissions over the NYCB cycle are presented in Figure 15. Again, Shell's GTL Fuel reduced emissions over the NYCB cycle versus the CARB specification diesel fuel. Additional emission reductions were observed with Shell's GTL Fuel and the CCRT filters.

Over both test cycles, tandem NO_x analyzers were employed to calculate the NO_2 emission.[11] The calculated NO_2 emissions are the difference between the NO_x and NO emissions. Using this method, the calculated NO_2 emissions were similar for the CARB specification diesel fuel and Shell's GTL Fuel without the filter. By employing the CCRT filter, the calculated NO_2 emissions increased significantly to ~50% of the total NO_x emissions. This trend was observed for both the CSHVR cycle and the NYCB cycle.

NREL/PIX 14086

Figure 11. Yosemite Waters vehicle on WVU chassis dynamometer

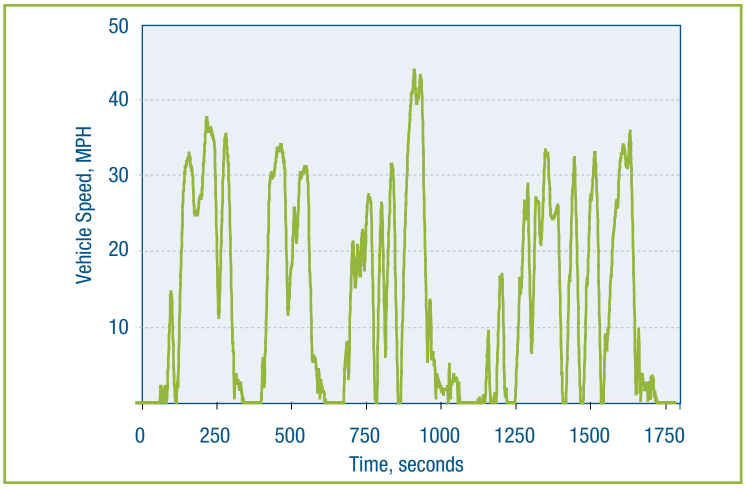

Figure 12. Schematic of the CSHVR test cycle

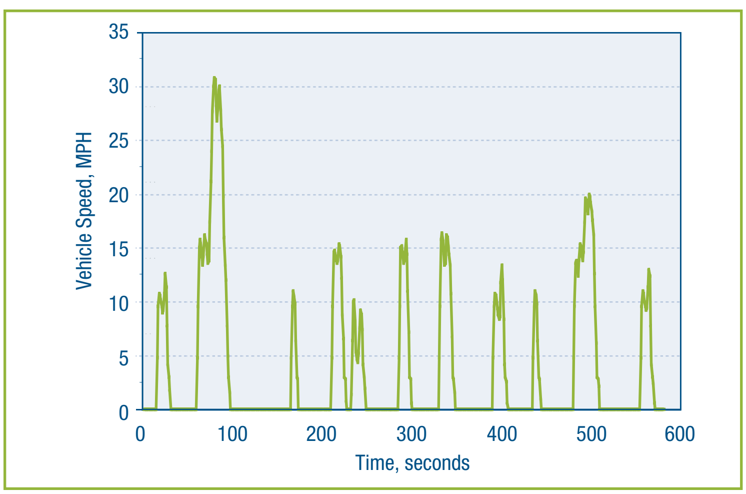

Figure 13. Schematic of the NYCB test cycle

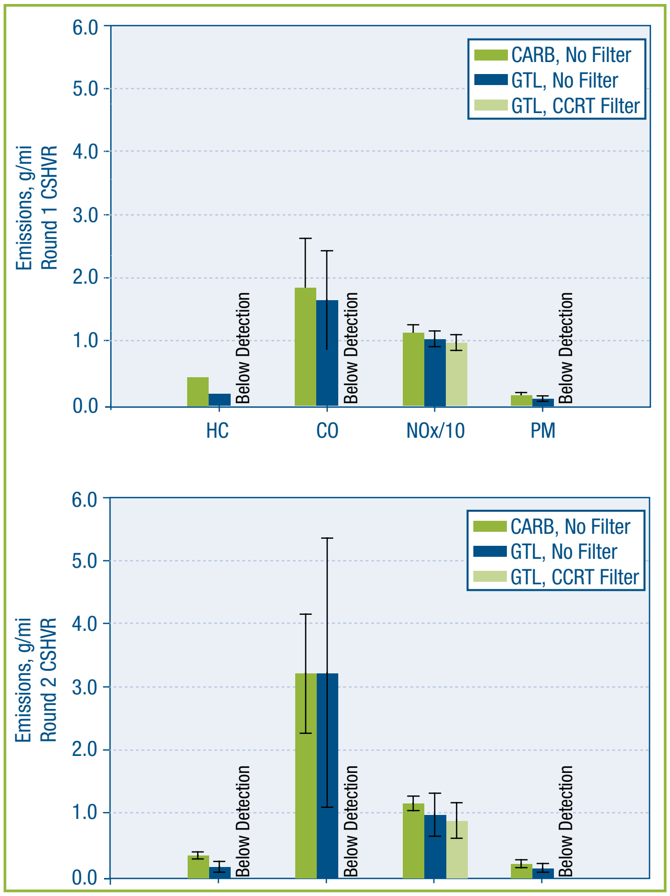

Figure 14. Emission test results for rounds 1 and 2 for CSHVR cycle

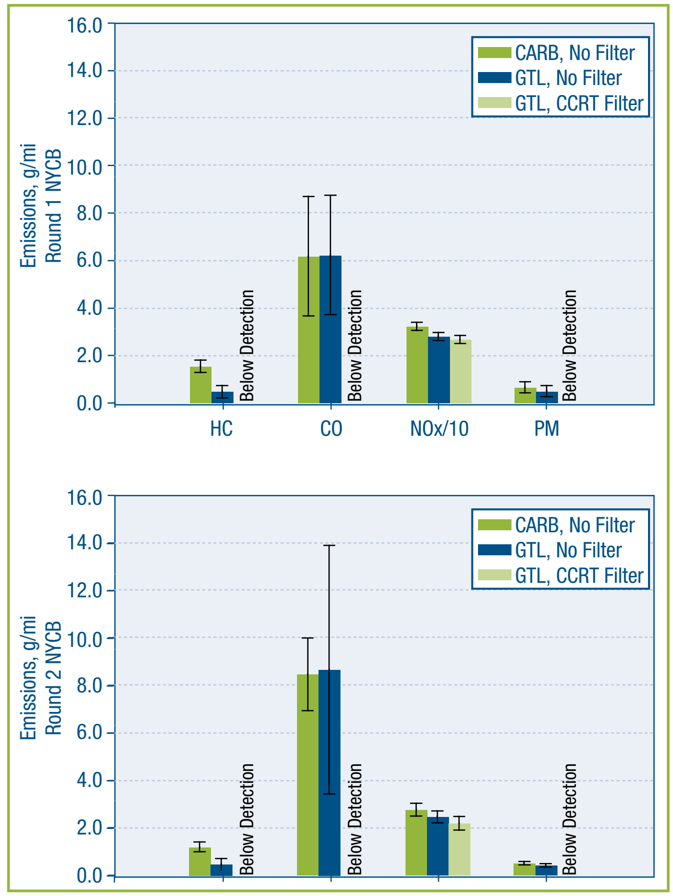

Figure 15. Emission test results for rounds 1 and 2 for NYCB cycle

Summary and Conclusions

Based on the evaluation of Shell's GTL Fuel in Yosemite Waters vehicles, the following conclusions were drawn relative to start-up issues and in-service testing.

Start-Up Issues

- Set-up and installation of on-site fueling tanks requires permits and approvals of local officials. Allow extra time when beginning a project. Working with local fire officials in advance of the project can help expedite the process.
- Retrofitting diesel particulate filters requires matching the filter properties to the fleet characteristics. Monitoring the filter in use can provide useful data about its efficacy through temperature profiles and back pressure measurements.
- Filters are intended to replace the muffler on a standard vehicle. Each specific model will require engineering to ensure proper fit and operation to avoid the damage experienced by Yosemite Waters.

In-Service Evaluation

- In general, the trucks fueled with GTL fuel performed similarly to the trucks fueled with CARB specification diesel fuel. Operators reported no noticeable difference in acceleration or power.
- Although the fuel economy for the GTL-fueled trucks was 8% lower than the diesel group, analysis showed this difference was not statistically significant.
- The GTL-fueled group showed a higher overall maintenance cost than the diesel group because of a starter problem with one specific vehicle. Failure of the starter on a vehicle is not likely caused by the use of the GTL fuel. If this data point is removed from the calculations, the difference in maintenance costs is not significant.

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Acronyms and Abbreviations

BTU	British thermal units
CARB	California Air Resources Board
CCRT®	Catalyzed Continuously Regenerating Technology
CSHVR	City Suburban Heavy Vehicle Route
CO	Carbon monoxide
CO_2	Carbon dioxide
ºC	Degrees Celsius
DOE	U.S. Department of Energy
EPAct	Energy Policy Act of 1992
FTD	Fischer-Tropsch diesel
ft-lb	foot pound
gal	gallon
g/mi	Grams per mile
g/mL	Grams per milliliter
GTL	Gas-to-liquid
HC	Hydrocarbons
hp	Horsepower
lb	Pound
JM	Johnson Matthey
mm	Millimeter
mm^2	Millimeter squared
MPG	Miles per gallon
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
NYCB	New York City Bus
PM	Particulate matter
ppm	Parts per million
SAE	Society of Automotive Engineers
SCAQMD	South Coast Air Quality Management District
WVU	West Virginia University

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2. "Fuel Properties of GTL Fuel and Emissions Results from a Fleet of Class 6 Trucks with Catalyzed Diesel Particulate Filters," presented at 14th CRC On-Road Emissions Workshop, San Diego, CA, March 24-25, 2004.

3. "Operability and Emissions from a Medium Duty Fleet Operating with GTL Fuel and Catalyzed DPFs" presented at 10th DEER Workshop, San Diego, CA, August 30, 2004.

4. "Comparison of Two Rounds of Emission Testing from a Fleet of Class 6 Trucks with GTL Fuel and Catalyzed DPFs," poster at 15th CRC On-Road Emissions Workshop, San Diego, CA, April 4, 2005.

Appendix A: Fleet and Summary Statistics

Fleet Operations and Economics		
	CARB diesel	**GTL Fuel**
Number of Vehicles	3	3
Period used for Analysis	1/04-7/04	1/04-7/04
Total Number of Months in Period	7	7
Analysis Base Fleet Mileage	34,473	29,822
Average Monthly Miles per Vehicle	1,691	1,555
Fleet Fuel Use (gal)	4,715	4,403
Representative Fleet MPG	7.31	6.77
Total Maintenance Cost per Mile	$0.025	$0.049
Total Maintenance Cost per Mile--Adjusted for Outlier	$0.025	$0.019
t Critical two-tail	2.306	

Detailed Fuel Analysis			
		Baseline Trucks	**Test Trucks**
Pre-Test Period All Trucks Using CARB Diesel	Number of Vehicles	3	3
	Fuel	CARB diesel	CARB diesel
	Filter Installed?	No	No
	Period Used for Analysis	1/02-11/02	1/02-11/02
	Analysis Base Mileage	44,965	42,376
	Fleet Fuel Used (gal)	6,174	5,916
	Fleet MPG	7.28	7.16
Mid-Test Period Test Trucks Using GTL Fuel--No Filters	Number of Vehicles	3	2
	Fuel	CARB diesel	GTL Fuel
	Filter Installed?	No	No
	Period Used for Analysis	3/03-11/03	3/03-11/03
	Analysis Base Mileage	43,326	28,201
	Fleet Fuel Used (gal)	6,099	4,204
	Fleet MPG	7.10	6.71
Test Period Test Trucks Using GTL Fuel with CCRT	Number of Vehicles	3	3
	Fuel	CARB diesel	GTL Fuel
	Filter Installed?	No	Yes
	Period Used for Analysis	1/04-7/04	1/04-7/04
	Analysis Base Mileage	34,473	29,822
	Fleet Fuel Used (gal)	4,715	4,403
	Fleet MPG	7.31	6.77

Appendix B: Emission Test Results

Vehicle	Round	Cycle	Fuel	Filter	Run #	CO, g/mi	NO_x, g/mi	NO_2, g/mi	HC, g/mi	PM, g/mi	CO_2, g/mi	Fuel Economy, MPG
201	1	CSHVR	CARB	None	2793-1	2.00	11.5		0.42	0.19	1461	6.86
					2793-2	1.91	11.6	1.3	0.48	0.19	1455	6.88
					2783-3	1.89	11.1	1.1	0.45	0.17	1414	7.09
					Average	**1.93**	**11.4**	**1.2**	**0.45**	**0.18**	**1443**	**6.94**
201	2	CSHVR	CARB	None	20073-1	3.17	13.0		0.37	0.23	1495	6.69
					20073-2	3.76	13.1	0.3	0.39	0.24	1513	6.61
					20073-3	3.78	12.6	0.5	0.36	0.24	1484	6.74
					Average	**3.57**	**12.9**	**0.4**	**0.37**	**0.24**	**1497**	**6.68**
202	1	CSHVR	CARB	None	2798-1	1.90	11.9		0.45	0.17	1417	7.07
					2798-2	2.15	11.6	1.1	0.52	0.17	1396	7.17
					2798-3	2.80	11.6	0.9	0.47	0.16	1403	7.14
					Average	**2.28**	**11.7**	**1.0**	**0.48**	**0.17**	**1405**	**7.13**
202	2	CSHVR	CARB	None	20080-1	3.31	12.2		0.41	0.26	1545	6.48
					20081-2	3.67	12.7	0.8	0.39	0.28	1585	6.31
					20081-3	3.67	12.6	0.6	0.39	0.27	1564	6.40
					Average	**3.55**	**12.5**	**0.7**	**0.40**	**0.27**	**1565**	**6.40**
203	1	CSHVR	CARB	None	2805-1	1.39	12.1		0.43	0.16	1476	6.79
					2805-2	1.36	11.7	1.1	0.47	0.15	1422	7.05
					2805-3	1.53	11.6	0.9	0.43	0.15	1408	7.12
					Average	**1.43**	**11.8**	**1.0**	**0.44**	**0.15**	**1435**	**6.99**
203	2	CSHVR	CARB	None	20056-1	2.56	10.7		0.32	0.19	1453	6.89
					20056-2	2.55	11.0	0.7	0.31	0.19	1450	6.90
					20056-3	2.50	10.7	0.4	0.31	0.19	1400	7.15
					Average	**2.54**	**10.8**	**0.5**	**0.31**	**0.19**	**1434**	**6.98**
203	2	CSHVR	CARB	None	20108-1	3.17	11.0		0.38	0.23	1510	6.63
					20108-2	2.92	10.9	0.2	0.37	0.21	1494	6.70
					20108-3	2.96	11.3	-0.5	0.35	0.22	1497	6.69
					Average	**3.02**	**11.1**	**-0.1**	**0.37**	**0.22**	**1500**	**6.67**
204	1	CSHVR	GTL	None	2837-2	2.33	11.1	0.1	0.24	0.16	1341	6.86
					2837-3	2.11	10.9	-0.4	0.24	0.15	1318	6.98
					2837-4	2.45	11.2		0.24	0.14	1312	7.01
					Average	**2.30**	**11.07**	**-0.15**	**0.24**	**0.15**	**1324**	**6.95**
204	2	CSHVR	GTL	None	20032-1	4.45	10.3		0.23	0.23	1363	6.73
					20032-2	5.05	10.3	0.6	0.22	0.22	1368	6.71
					20032-3	5.13	10.2	0.7	0.23	0.23	1329	6.9
					Average	**4.88**	**10.3**	**0.65**	**0.23**	**0.23**	**1353**	**6.78**
204	2	CSHVR	GTL	None	20135-1	4.04	9.9		0.22	0.24	1429	7.00
					20135-2	4.36	10.3	0.40	0.20	0.23	1421	7.03
					20135-3	4.23	10.4	0.70	0.20	0.21	1443	6.93
					Average	**4.21**	**10.20**	**0.55**	**0.21**	**0.23**	**1431**	**6.99**

Vehicle	Round	Cycle	Fuel	Filter	Run #	CO, g/mi	NO_x, g/mi	NO_2, g/mi	HC, g/mi	PM, g/mi	CO_2, g/mi	Fuel Economy, MPG
205	1	CSHVR	GTL	None	2820-1	1.26	9.5		0.16	0.10	1248	7.38
					2820-2	1.27	9.2	0.7	0.15	0.08	1208	7.63
					2820-3	1.32	9.2	0.6	0.14	0.09	1218	7.57
					Average	**1.28**	**9.3**	**0.6**	**0.15**	**0.09**	**1225**	**7.53**
205	2	CSHVR	GTL	None	20051-1	1.85	8.2		0.15	0.11	1156	7.97
					20051-2	2.11	8.6	0.4	0.16	0.11	1177	7.82
					20051-3	2.18	8.4	0.4	0.16	0.11	1155	7.97
					Average	**2.05**	**8.4**	**0.4**	**0.16**	**0.11**	**1163**	**7.92**
206	1	CSHVR	GTL	None	2828-1	1.55	11.6		0.15	0.11	1369	6.73
					2828-2	1.39	11.6	0.4	0.20	0.10	1375	6.70
					2828-3	1.45	11.2	0.3	0.21	0.09	1353	6.81
					Average	**1.46**	**11.5**	**0.4**	**0.19**	**0.10**	**1366**	**6.75**
206	2	CSHVR	GTL	None	20069-1	2.95	11.7		0.20	0.17	1583	5.82
					20069-2	2.73	11.9	0.5	0.18	0.15	1544	5.96
					20069-3	3.04	12.2	0.4	0.19	0.16	1559	5.90
					Average	**2.91**	**11.9**	**0.4**	**0.19**	**0.16**	**1562**	**5.89**
204	1	CSHVR	GTL	CCRT	2830-1	0.00	10.8		0.00	0.00	1364	6.77
					2830-2	0.08	10.8	5.9	0.00	0.00	1321	6.97
					2830-3	0.00	10.7	5.4	0.00	0.00	1321	6.99
					Average	**0.03**	**10.8**	**5.7**	**0.00**	**0.00**	**1335**	**6.91**
204	2	CSHVR	GTL	CCRT	20027-1	0.00	9.2		0.00	0.00	1340	6.89
					20027-2	0.00	9.2	4.5	0.00	0.00	1332	6.93
					20027-3	0.00	9.6	4.6	0.00	0.00	1322	6.99
					Average	**0.00**	**9.3**	**4.6**	**0.00**	**0.00**	**1331**	**6.94**
205	1	CSHVR	GTL	CCRT	2813-1	0.00	9.1		0.00	0.00	1268	7.29
					2813-2	0.00	8.7	4.5	0.00	0.00	1224	7.55
					2813-3	0.00	8.7	4.4	0.00	0.00	1220	7.57
					Average	**0.00**	**8.8**	**4.5**	**0.00**	**0.00**	**1237**	**7.47**
205	2	CSHVR	GTL	CCRT	20045-2	0.00	7.3	3.4	0.00	0.0016	1087	8.5
					20045-3	0.00	7.6	3.4	0.00	0.0010	1129	8.18
					20045-4	0.00	7.5		0.00	0.0007	1079	8.56
					Average	**0.00**	**7.5**	**3.4**	**0.00**	**0.0011**	**1098**	**8.41**
206	1	CSHVR	GTL	CCRT	2822-1	0.00	10.6		0.00	0.00	1409	6.56
					2822-2	0.00	10.3	5.8	0.00	0.00	1371	6.74
					2822-3	0.00	10.5	6.1	0.00	0.00	1369	6.75
					Average	**0.00**	**10.5**	**6.0**	**0.00**	**0.00**	**1383**	**6.68**
206	2	CSHVR	GTL	CCRT	20064-1	0.0125	10.2		0.00	0.0010	1413	6.54
					20064-3	0.0000	11.3	5.00	0.00	0.0008	1477	6.26
					20064-4	0.0042	11.1	5.00	0.00	0.0002	1425	6.48
					Average	**0.0056**	**10.9**	**5.00**	**0.00**	**0.001**	**1438**	**6.43**

Vehicle	Round	Cycle	Fuel	Filter	Run #	CO, g/mi	NO_x, g/mi	NO_2, g/mi	HC, g/mi	PM, g/mi	CO_2, g/mi	Fuel Economy, MPG
201	1	NYCB	CARB	None	2792-1	5.09	31.9		1.56	0.61	3890	2.57
					2792-2	5.52	32.3	4.0	1.37	0.55	3856	2.69
					2792-3	6.18	30.7	3.2	1.54	0.56	3940	2.54
					Average	**5.60**	**31.6**	**3.6**	**1.49**	**0.57**	**3895**	**2.60**
201	2	NYCB	CARB	None	20074-1	10.68	32.2		1.31	0.62	3826	2.61
					20074-2	8.95	30.3	2.4	1.35	0.53	3657	2.73
					20074-3	9.79	31.6	1.8	1.33	0.49	3789	2.64
					Average	**9.81**	**31.37**	**2.10**	**1.33**	**0.55**	**3757**	**2.66**
202	1	NYCB	CARB	None	2797-1	6.26	33.3		1.48	0.67	3932	2.55
					2797-2	6.92	34.5	3.2	1.34	0.63	4073	2.46
					2797-3	9.35	32.3	3.9	1.33	0.80	3857	2.59
					Average	**7.51**	**33.4**	**3.6**	**1.38**	**0.70**	**3954**	**2.53**
202	2	NYCB	CARB	None	20079-1	8.18	27.3		1.38	0.55	3644	2.74
					20079-2	7.93	26.9	3.5	1.23	0.54	3595	2.78
					20079-3	8.50	26.7	3.1	1.20	0.57	3556	2.81
					Average	**8.20**	**27.0**	**3.3**	**1.27**	**0.55**	**3598**	**2.78**
203	1	NYCB	CARB	None	2802-1	4.68	32.1		1.56	0.80	3988	2.51
					2802-2	5.41	31.9	3.3	1.87	0.65	3997	2.50
					2802-3	6.25	32.0	2.9	1.84	0.65	4072	2.46
					Average	**5.45**	**32.0**	**3.1**	**1.76**	**0.70**	**4019**	**2.49**
203	2	NYCB	CARB	None	20055-1	6.80	26.1		1.03	0.45	3681	2.72
					20055-2	6.94	26.7	2.4	1.00	0.49	3593	2.79
					20055-3	7.13	26.5	1.5	1.10	0.51	3697	2.71
					Average	**6.96**	**26.4**	**1.95**	**1.04**	**0.48**	**3657**	**2.74**
203	2	NYCB	CARB	None	20107-1	9.52	26.8		1.31	0.56	3747	2.67
					20107-2	9.02	26.1	2.3	1.33	0.56	3671	2.72
					20107-3	8.38	26.3	0.3	1.00	0.50	3719	2.69
					Average	**8.97**	**26.4**	**1.3**	**1.21**	**0.54**	**3712**	**2.69**
204	1	NYCB	GTL	None	2835-1	7.55	28.3		0.55	0.92	3650	2.52
					2835-2	8.76	29.4	2.9	0.65	0.63	3617	2.54
					2835-3	8.94	28.0	1.3	0.63	0.61	2561	2.58
					Average	**8.4**	**28.6**	**2.1**	**0.6**	**0.7**	**3276**	**2.5**
204	2	NYCB	GTL	None	20031-1	10.3	23.0	1.2	0.62	0.55	3401	2.70
					20031-2	12.5	24.4		0.62	0.54	3474	2.64
					20031-3	11.1	23.9	2.1	0.59	0.51	3367	2.73
					Average	**11.3**	**23.8**	**1.65**	**0.61**	**0.53**	**3414**	**2.69**
204	2	NYCB	GTL	None	20134-1	11.2	24.2		0.50	0.55	3620	2.54
					20134-2	11.5	25.0	1.7	0.47	0.55	3674	2.5
					20134-3	11.1	24.3	2.2	0.65	0.57	3523	2.61
					Average	**11.27**	**24.50**	**1.95**	**0.54**	**0.56**	**3606**	**2.55**

Vehicle	Round	Cycle	Fuel	Filter	Run #	CO, g/mi	NO_x, g/mi	NO_2, g/mi	HC, g/mi	PM, g/mi	CO_2, g/mi	Fuel Economy, MPG
205	1	NYCB	GTL	None	2819-1	5.56	26.6		0.28	0.37	3479	2.65
					2819-2	4.91	26.3	2.4	0.36	0.36	3494	2.64
					2819-3	5.33	26.8	1.9	0.42	0.30	3588	2.57
					Average	**5.27**	**26.57**	**2.15**	**0.35**	**0.34**	**3520**	**2.62**
205	2	NYCB	GTL	None	20050-1	8.04	24.1		0.39	0.35	3466	2.65
					20050-2	7.26	24.2	1.7	0.43	0.33	3419	2.69
					20050-3	6.93	23.9	1.3	0.40	0.33	3402	2.71
					Average	**7.41**	**24.1**	**1.5**	**0.41**	**0.34**	**3429**	**2.68**
206	1	NYCB	GTL	None	2826-1	4.58	27.8		0.33	0.48	3572	2.58
					2826-2	5.59	29.0	1.5	0.54	0.46	3701	2.49
					2826-3	4.89	29.8	1.6	0.54	0.40	3856	2.39
					Average	**5.02**	**28.9**	**1.6**	**0.47**	**0.45**	**3710**	**2.49**
206	2	NYCB	GTL	None	20068-1	7.32	26.2		0.45	0.37	3799	2.42
					20068-2	6.94	26.2	1.9	0.47	0.33	3771	2.44
					20068-3	7.35	27.0	1.3	0.52	0.38	3838	2.40
					Average	**7.20**	**26.5**	**1.6**	**0.48**	**0.36**	**3803**	**2.42**
204	1	NYCB	GTL	CCRT	2833-1	0.00	28.2		0.00	0.01	3229	2.62
					2833-2	0.00	28.6	15.9	0.00	0.01	3615	2.56
					2833-3	0.00	27.1	15.3	0.00	0.00	3535	2.61
					Average	**0.00**	**27.97**	**15.60**	**0.00**	**0.01**	**3460**	**2.60**
204	2	NYCB	GTL	CCRT	20026-1	0.00	20.40		0.03	0.00	3261	2.83
					20026-2	0.21	20.10	11.00	0.00	0.00	3215	2.87
					20026-3	0.00	19.20		0.01	0.00	3098	2.98
204	2	NYCB	GTL	CCRT	20036-1	0.043	21.3		0.00	0.0077	3394	2.72
					20036-2	0.000	21.5	11.6	0.00	0.0044	3364	2.75
					20036-3	0.000	21.8		0.00	0.0056	3318	2.78
					Average	**0.014**	**21.5**	**11.6**	**0.00**	**0.0059**	**3359**	**2.75**
205	1	NYCB	GTL	CCRT	2809-1	0.00	25.9		0.00	0.0510	3609	2.56
					2809-2	0.00	25.7	12.5	0.00	0.0170	3595	2.57
					2809-3	0.00	24.8	11.1	0.00	0.0170	3520	2.62
					Average	**0.00**	**25.5**	**11.8**	**0.00**	**0.0283**	**3575**	**2.58**
205	2	NYCB	GTL	CCRT	20041-1	0.00	21.2		0.00	0.0046	3239	2.85
					20041-2	0.00	21.9	8.9	0.00	0.0045	3339	2.77
					20041-3	0.00	22.0	10.1	0.00	0.0073	3267	2.83
					Average	**0.00**	**21.7**	**9.5**	**0.00**	**0.0055**	**3282**	**2.82**
206	1	NYCB	GTL	CCRT	2823-1	0.00	25.80		0.00	0.007	3388	2.73
					2823-2	0.00	27.80	13.4	0.00	0.002	3593	2.57
					2823-3	0.00	27.40	12.2	0.00	0.061	3516	2.63
					Average	**0.00**	**27.00**	**12.8**	**0.00**	**0.023**	**3499**	**2.64**
206	2	NYCB	GTL	CCRT	20060-2	0.00	25.40		0.00	0.014	3538	2.61
					20060-3	0.00	25.50	11.4	0.00	0.012	3572	2.59
					20060-4	0.00	25.00	10.9	0.00	0.015	3454	2.61
					Average	**0.00**	**25.30**	**11.2**	**0.00**	**0.014**	**3521**	**2.60**

NREL/BR-540-38195
August 2005

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