Advanced Technology Vehicle Evaluation

Advanced Vehicle Testing Activity

FreedomCAR

FreedomCAR & Vehicle Technologies Program

Norcal Prototype LNG Truck Fleet

Final Results

U.S. Department of Energy

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NORCAL PROTOTYPE LNG TRUCK FLEET: FINAL RESULTS

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Executive Summary

Norcal Waste Systems, Inc. provides services in refuse collection, recycling, waste transfer, and landfill operations to more than 50 communities in the San Francisco area. In 2001, Norcal's subsidiary SF Recycling & Disposal began operating 14 heavy-duty liquefied natural gas (LNG) waste transfer trucks equipped with prototype Cummins Westport, Inc. (CWI) ISXG engines. The LNG trucks were evaluated over 2 years of operation as part of the U.S. Department of Energy's (DOE's) Advanced Vehicle Testing Activity (AVTA). Diesel trucks were also evaluated over part of this period for comparison purposes. This report summarizes the results of the prototype LNG truck evaluation at Norcal.

Objectives

AVTA provides unbiased information about alternative fuel and advanced transportation technologies that reduce U.S. dependence on foreign oil while improving the nation's air quality. AVTA's objective for this project was to determine how close the ISXG is to commercialization and what design changes and integration work might be required to bring the technology to a commercial level of reliability.

The project partners, CWI and Norcal, have been dedicated to making this deployment of new technology LNG trucks successful. However, each company had slightly different objectives for the project because of its own perspective and expectations. For CWI, the objective was to integrate the prototype natural gas engine into a standard Class 8 heavy truck, then to field test the technology and determine areas that require more engineering work. For Norcal, the objective was to successfully implement the LNG trucks into standard operation. Cost was not a major concern during the prototype phase because parts were covered under a demonstration agreement; however, Norcal expects the operating and maintenance costs to be reduced significantly in order to deploy more of this technology in the future.

Technology

The ISXG engine, which was specifically developed for use with LNG, uses the Westport-Cycle™ high-pressure direct injection (HPDI) fuel system. In this system, LNG is pumped up to high pressure, vaporized, and delivered to the engine at approximately 3,000 psi along with a small amount of diesel that ignites the natural gas in a compression-ignition (diesel) cycle. The engine cannot operate on diesel alone unless the Westport-Cycle HPDI natural gas fuel system and injectors are removed and replaced with standard diesel equipment.

Methods

Data were collected and evaluated for three groups of trucks, including 12 LNG trucks, seven new diesel trucks, and five older diesel trucks:

- Diesel fuel consumption by vehicle
- LNG fuel consumption by vehicle
- Mileage data from every vehicle
- Engine oil additions and filter changes
- Preventive maintenance action work orders, parts lists, labor records, and related documents
- Records of unscheduled maintenance (such as road calls)
- Records of repairs covered by the prototype demonstration agreement.

Results

The following is a summary of the evaluation results:

- Drivers reported that the performance of the LNG trucks was as good as or better than that of the diesel trucks.
- The LNG trucks were operated more than 1.8 million miles through July 2003 and

What's New About This LNG Engine Technology?

Most heavy-duty natural gas engines use a spark-ignition cycle. Diesel engines use a compression-ignition cycle, which provides better engine efficiency and low-speed torque response in most heavy vehicle applications compared with a spark-ignition cycle. Natural gas alone does not work well in compression-ignition engines. To overcome this, the Westport-Cycle HPDI technology injects a small amount of diesel into the engine cylinder to provide compression ignition for the natural gas. Thus, the engine gains the advantages of compression-ignition while consuming natural gas as its primary fuel.

were projected to operate 2.3 million miles through December 2003. The LNG trucks have been used at a rate of 100,000 miles per month. This high use rate for the LNG trucks indicates improving reliability.

- The LNG trucks were used nearly as much as the diesel trucks in the same operation, with average monthly mileage 9% lower during the evaluation period. This is much better than previous results from other LNG truck operations, in which other LNG trucks typically were used 25% less than diesel trucks*.
- The energy equivalent fuel economy was 10.5% lower for the prototype LNG trucks compared with the newest diesel trucks. This is much better than results from previous studies of spark-ignition, heavy-duty natural gas trucks, which had equivalent fuel economies 27%–37% lower than diesel trucks over the same duty cycle*.
- Maintenance costs for the prototype LNG trucks were 2.3 times higher per mile than for the newest commercial diesel trucks. This was expected because the LNG engine technology is in the prototype stage. For CWI, one objective of this project was to study ways to enhance reliability of this new potential product. The components and systems with maintenance issues were the LNG pump, high-pressure diesel fuel system, and HPDI injectors. CWI continues to plan better integration strategies for these and other related components.
- Nearly 90% of the road calls for the LNG trucks were due to the engine- and fuel-related systems (non-lighting electrical, air intake, cooling, exhaust, fuel, engine, and hydraulic systems). The mileage between road calls began to improve after an issue with the onboard LNG tanks losing vacuum began to be resolved.
- Use of "clean" LNG was a major concern. Contaminants in LNG pose a threat to high-pressure LNG pumps and onboard injectors. CWI implemented additional filtration on the trucks and worked with Clean Energy to implement additional filtration at the fueling station. CWI plans to make changes to the LNG pump and onboard fuel system to alleviate some of the sensitivity to contaminants.
- The high cost of LNG used in the evaluation resulted mainly from delivery costs from Wyoming to San Francisco. Producing LNG nearby or constructing an import terminal would alleviate much of this cost. Energy suppliers are exploring these options.

Future Plans

Originally, CWI and Norcal planned to upfit nine new ISX diesel trucks with a new version of the LNG fuel system and engine. These trucks were to be early commercial versions of this propulsion system. However, CWI recently decided to delay the commercial release of the ISXG engine owing to market conditions.

CWI intends to reduce the ISXG's oxides of nitrogen (NO_x) emissions to 0.2 grams per brake horsepower hour (g/bhp-hr) and hopes to introduce it commercially in the 2007-2008 timeframe. The next round of demonstrations is expected in 2005 and may include a market development demonstration of a 1.2 g/bhp-hr NO_x engine and a technology demonstration at the 0.2 g/bhp-hr NO_x level.

Future ISXG engines also will include an improved LNG pump and more robust HPDI injectors. The improved pump is expected to reduce complications due to debris in the fuel. The more robust HPDI injectors are expected to reduce the rate of injector failure significantly. New hardware and calibrations will improve efficiency, and a higher-power (450 hp) engine rating may be available. CWI also has significant integration and packaging engineering work planned for the truck platform to reduce maintenance costs and increase reliability.

Norcal currently has no plans to purchase additional LNG trucks. However, the LNG trucks at SF Recycling & Disposal are currently operating in the configuration described in this report. Some additions and changes may be made to the high-pressure fuel systems, and CWI will continue to support Norcal's LNG trucks.

* *Raley's LNG Truck Fleet Final Results*, 2000, NREL/BR-540-27678; *Waste Management's LNG Truck Fleet Final Results*, 2001, NREL/BR-540-29073. Visit **www.eere.energy.gov/cleancities/afdc** to obtain these publications.

Overview

With more than 1,800 employee owners, California's Norcal Waste Systems, Inc. is the largest employee-owned waste management company in the United States. It provides services in refuse collection, recycling, waste transfer, and landfill operations to more than 50 communities in the San Francisco area, including 460,000 residential, commercial, and industrial customers.

In 2001, in response to impending emission reduction mandates, Norcal began operating 14 heavy-duty liquefied natural gas (LNG) waste transfer trucks equipped with prototype Cummins Westport, Inc. (CWI) ISXG engines. Waste transfer trucks are large tractor-trailers that collect garbage from a central location and truck it to the landfill, spending most of their driving time on the highway.

The LNG trucks were evaluated over 2 years of operation as part of the U.S. Department of Energy's (DOE's) Advanced Vehicle Testing Activity (AVTA). Diesel trucks were also evaluated for comparison purposes. This report summarizes the results of the prototype LNG truck evaluation at Norcal.

What Is LNG Fuel and How Is It Processed?

Liquefied natural gas is a naturally occurring mixture of hydrocarbons (mainly methane, or CH_4), that has been purified and condensed to liquid form by cooling cryogenically to -260°F (-162°C). At atmospheric pressure, it occupies only 1/600 the volume of natural gas in vapor form.

Methane is the simplest molecule of the fossil fuels and can be burned very cleanly. It has an octane rating of 130 and excellent properties for spark-ignited internal combustion engines.

Because it must be kept at such cold temperatures, LNG is stored in double-wall, vacuum-insulated pressure vessels. Compared to the fuel tanks required for using compressed natural gas (CNG) in vehicles operating over similar ranges, LNG fuel tanks are smaller and lighter. However, they are larger, heavier, and more expensive than diesel fuel tanks.

Compared to conventional fuels, LNG's flammability is limited. It is nontoxic, odorless, noncorrosive, and noncarcinogenic. It presents no threat to soil, surface water, or groundwater.

LNG is used primarily for international trade in natural gas and for meeting seasonal demands for natural gas. It is produced mainly at LNG storage locations operated by natural gas suppliers, and at cryogenic extraction plants in gas-producing states. Only a handful of large-scale liquefaction facilities in the United States provide LNG fuel for transportation.

This information was adapted from the following Web sites. Each offers further information about LNG:
– Natural Gas Vehicle Coalition: www.ngvc.org
– Alternative Fuels Data Center: www.eere.energy.gov/cleancities/afdc
– Zeus Development Corp./LNG Express: www.lngexpress.com
– CH-IV Cryogenics: www.ch-iv.com/lng/lngfact.htm

DOE's Advanced Vehicle Testing Activity

AVTA provides unbiased information about alternative fuel and advanced transportation technologies that reduce U.S. dependence on foreign oil while improving the nation's air quality. The role of the activity is to bridge the gap between R&D and commercial availability of advanced vehicle technologies. AVTA supports DOE's FreedomCAR and Vehicle Technologies Program in moving these technologies from R&D to market deployment by examining market factors and customer requirements, evaluating performance and durability of alternative fuel and advanced technology vehicles, and assessing the performance of these vehicles in fleet applications.

The Fleet Test & Evaluation team at the National Renewable Energy Laboratory (NREL) supports AVTA by conducting medium- and heavy-duty vehicle evaluations. The team's tasks include identifying fleets to evaluate, mutually agreeing on the type of commercial alternative fuel vehicles to test, designing test plans, gathering the on-site data, preparing technical reports, and communicating results on its Web site and in print publications. The primary target audience for AVTA evaluations includes operators who are using or may consider using these advanced technologies. NREL has completed numerous light- and heavy-duty vehicle evaluations based on an established data collection protocol developed with and for DOE*.

* *General Evaluation Plan: Fleet Test & Evaluation Projects*, 2002, NREL/BR-540-32392. Visit **www.eere.energy.gov/cleancities/afdc** to obtain this publication.

Host Site Profile: Norcal Waste Systems, Inc.

Norcal was established in 1921 in San Francisco and now operates 22 subsidiary companies. In San Francisco, Norcal companies include Golden Gate Disposal & Recycling Company, Sunset Scavenger Company, and SF Recycling & Disposal (formerly known as Sanitary Fill Company).

Each of the Norcal companies in San Francisco offers recycling of more than a dozen commodities, from curbside bins and yard waste collection to materials recovery. Recycling is emphasized to reduce consumption of virgin materials and save landfill space. Golden Gate Disposal & Recycling Company provides recycling programs for paper and other materials to high-rise office buildings and downtown businesses. Sunset Scavenger Company collects commingled recyclables through the curbside program. SF Recycling & Disposal operates a construction and debris sorting line, provides transfer operations to the landfill for non-recyclable materials, and operates a household hazardous waste center. The primary landfill operation for San Francisco is in Livermore, California.

PIX 13172

Figure 1. Transfer Trucks at SF Recycling & Disposal

Norcal recently started to compost food scraps and other organic materials, which would otherwise have been sent to the landfill, as part of its recycling programs. The composting provides organic material for agriculture and soil replenishment. Norcal has also upgraded and consolidated recycling activities at Recycle Central (Pier 96) in San Francisco.

Norcal began using LNG trucks to investigate cleaner emission technology before such technology was mandated by local and state government regulations. Implementation and evaluation of the trucks was supported through grants and in-kind contributions from the City and County of San Francisco, the Bay Area Air Quality Management District, CWI, Cummins West, Clean Energy Fuels, and NexGen Fueling. For Norcal, the objectives of using the trucks included the following:

- Reduce emissions significantly
- Prove that this LNG technology can perform adequately, particularly in terms of reliability and power
- Continue to promote and enhance a "green" public image.

The LNG trucks became part of a fleet of 38 transfer trucks at Norcal's subsidiary SF Recycling & Disposal (Figure 1). Non-recyclable garbage from the City and County of San Francisco arrives at SF Recycling & Disposal, where it is put into large transfer trailers and trucked to the landfill for environmentally safe disposal. Recyclables are collected and transferred to commodity receivers. In March 2002, SF Recycling & Disposal opened a permanent LNG fueling station, the first LNG fueling station in the Bay Area.

Norcal's Prototype LNG Trucks

As mentioned previously, Norcal operates 14 LNG heavy trucks; however, evaluation results for only 12 of the LNG trucks are reported here. The other two trucks were designed and set up to operate in a significantly different duty cycle, were equipped with larger LNG fuel tanks, and had hydraulics added for a trailer used to deliver recyclable materials and liquid/wet materials. The evaluation at Norcal included new diesel trucks equipped with the diesel version of the

Cummins ISX engine and older diesel trucks equipped with the Cummins N14 diesel engine. Two of the nine new diesel trucks were equipped for the same type of recyclable material transport as the two excluded LNG trucks and were also excluded from the detailed evaluation results. See the Appendix for results from the excluded trucks. The vehicles in this report included the following:

- 12 LNG trucks—Peterbilt model 378 truck, CWI ISXG engine
- 5 older diesel trucks—Peterbilt model 378 truck, Cummins N14 engine
- 7 new diesel trucks—Peterbilt model 378 truck, Cummins ISX engine with cooled exhaust gas recirculation (EGR).

Table 1 shows a summary of vehicle system descriptions for the three groups of trucks. The truck model is the same for all three groups. The engines are slightly different, but nearly everything about the trucks except the LNG fuel system is essentially the same.

The five older diesel trucks were included in this evaluation to compare vehicle use and fuel economy with the LNG trucks and the new diesel trucks, representing operations at SF Recycling & Disposal before the LNG trucks and the newer diesel trucks started operation.

The Prototype ISXG Engine with Westport-Cycle HPDI Fuel System

Norcal's LNG trucks were equipped with prototype CWI ISXG engines. CWI is a joint venture between Cummins, Inc. and Westport Innovations, Inc., formed to commercialize natural gas engines. Westport Innovations developed the Westport-Cycle high-pressure direct injection (HPDI) fuel system for natural gas engines. Cummins is a veteran diesel engine manufacturer that provides compression-ignition (diesel) engines for heavy-duty vehicle applications.

Most heavy-duty natural gas engines use a spark-ignition cycle. Diesel engines use a compression-ignition cycle, which provides better engine efficiency and low-speed torque response in most heavy vehicle applications compared with a spark-ignition cycle. Natural gas alone does not work well in compression-ignition engines. The Westport-Cycle HPDI system enables the ISXG engine to operate on a compression-ignition cycle while using natural gas as the main fuel (Figure 2).

Table 1. Vehicles Used in the Evaluation

Vehicle Systems	LNG Trucks	New Diesel Trucks	Old Diesel Trucks
Number of Vehicles	12	7	5
Fuel(s) Used	LNG, Diesel	Diesel	Diesel
Truck Manufacturer/Model	Peterbilt/378	Peterbilt/378	Peterbilt/378
Truck Year	2001	2002	1998
GVWR/GCWR (lb)	46,000/80,000	46,000/80,000	46,000/80,000
Engine Manufacturer/Model	Cummins/ISXG	Cummins/ISX	Cummins/N14
Engine Year	2001	2003	1999
Engine Rating Rated Horsepower Maximum Torque	 400 hp @ 1,800 rpm 1,450 lb-ft @ 1,200 rpm	 400 hp @ 1,800 rpm 1,450 lb-ft @ 1,200 rpm	 350 hp @ 1,800 rpm 1,400 lb-ft @ 1,200 rpm
Displacement	14.9 L	14.9 L	14.0 L
Transmission Manufacturer/Model	Fuller/RTL014610B	Fuller/RTL014610B	Fuller/RTL014610B
Fuel System Capacity Diesel LNG	 50 gal 75 gal	 50 gal -	 50 gal -
Emission Control Equipment	None	EGR	None

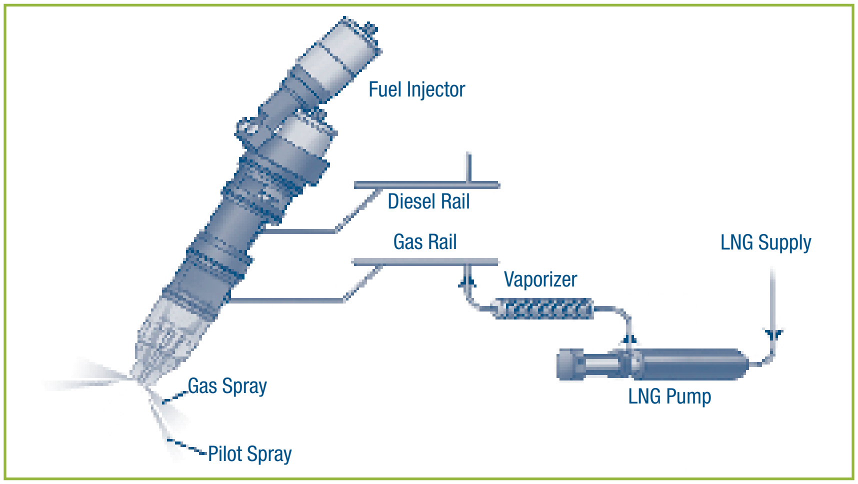


Figure 2. HPDI Fuel System on LNG Truck

In this system, LNG is pumped up to high pressure, vaporized, and delivered to the engine at approximately 3,000 psi along with a small amount of high-pressure diesel. The diesel and natural gas are injected simultaneously into each cylinder through a single fuel injector, which fits in the same space as a diesel fuel injector. The diesel provides ignition for the natural gas in the compression ignition cycle. Currently, 6%–7% of the energy content used by the prototype ISXG engine is from diesel. The engine cannot operate on diesel alone unless the Westport-Cycle HPDI natural gas fuel system and injectors are removed and replaced with standard diesel equipment.

The Westport-Cycle HPDI technology provides diesel-like power—the prototype ISXG can generate more than 500 hp—and engine response; however, the engines used at Norcal have been electronically set to a maximum of 400 hp. In addition, this system comes much closer to attaining diesel-like efficiency than spark-ignited natural gas systems can. The torque and horsepower curves for the ISX diesel engine and ISXG natural gas engines have the same shape.

Engines using the Westport-Cycle HPDI system can also provide emissions benefits. In February 2001, the California Air Resources Board certified CWI's prototype ISXG engines to 2.4 grams per brake horsepower hour (g/bhp-hr) oxides of nitrogen (NO_X).

Table 2 shows the certification levels for the model year 2001 prototype ISXG engine and ISX diesel engine. The ISXG engines were certified to NO_X levels 35% lower, and particulate matter levels 38% lower, than the ISX diesel engine.

The newest diesel trucks included in this evaluation used model year 2003 ISX diesel engines. In April 2002, Cummins announced that the ISX was the first diesel on-highway engine slated for the October 2002 emissions standard to be certified by the U.S. Environmental Protection Agency to the 2.5 g/bhp-hr NO_X + NMHC (non-methane hydrocarbons) standard. The model year 2003 ISX diesel engine uses cooled EGR to help control NO_X emissions.

Project Design and Data Collection

CWI and Norcal have been dedicated to making this deployment of new technology LNG trucks successful. However, each company had slightly different objectives for the project because of its own perspective and expectations.

For CWI, the objective was to integrate the prototype HPDI natural gas engine into a standard Class 8 heavy truck, then to field test the technology and determine areas that require more engineering work. One of the most challenging aspects of this project was the integration of HPDI-related equipment. This project allowed CWI to study the integration and operation before commercial release of the technology in this trucking vocation. CWI stationed technicians on site at Norcal to monitor the LNG trucks, collect engineering data, and provide support and training to the Norcal mechanics to keep the trucks operating well.

For Norcal, the objective was to successfully implement the LNG trucks into standard operation. Norcal has been dedicated to supporting the technology and required training for this operation. Over time, Norcal expects the operating and maintenance costs, as well as reliability, to become similar to the diesel trucks currently in use at the site. However, Norcal understands the need to develop this technology to maturity. Norcal was interested in this natural gas engine technology because of the potential for diesel-like fuel economy and power.

Table 2. California Air Resources Board Emissions Certification Levels (g/bhp-hr)							
Model Year	Fuel	THC	NMHC	NO_x	CO	PM	Engine Family
2001	Certification Levels	1.3	1.2	4.0	15.5	0.10	All
2001 ISX	Diesel	0.1	-	3.7	0.5	0.08	1CEXH0912XAC
2001 ISXG	Natural Gas	-	0.4	2.4	2.0	0.05	1WFSH0912XAC
2003	Certification Levels	-	2.4, 2.5*		15.5	0.10	All
2003 ISX	Diesel**	-	2.4		1.0	0.08	3CEXH0912XAH

* 2.4 g/bhp-hr THC + NO_x standard for diesel, 2.5 g/bhp-hr NMHC + NO_x standard for natural gas.
** Uses cooled EGR.

The objectives of AVTA evaluation projects focus on using a standardized process for data collection and analysis, communicating results clearly, and providing an accurate and complete evaluation. To accomplish these objectives for this project, the LNG trucks were evaluated via data collection and evaluation of the prototype trucks, the older diesel trucks, and the new diesel trucks. Data were taken from data collection systems used at SF Recycling & Disposal for truck assignments, fuel consumption, and maintenance. Data parameters included the following:

- Diesel fuel consumption by vehicle
- LNG fuel consumption by vehicle
- Mileage data from every vehicle
- Engine oil additions and filter changes
- Preventive maintenance action work orders, parts lists, labor records, and related documents
- Records of unscheduled maintenance (such as road calls)
- Records of repairs covered by the prototype demonstration agreement.

The data collection was designed to cause as little disruption for Norcal and SF Recycling & Disposal as possible. Data were sent from the truck site to Battelle for analysis. In general, staff at SF Recycling & Disposal sent copies (electronic or paper) of data that had already been collected as part of normal business operations.

Staff from SF Recycling & Disposal and CWI had access to all data being collected from the site and other data available from the project. Summaries, evaluations, and analyses of the data were distributed to designated staff for review and input.

The study design included tracking of safety incidents that affected the vehicles or that occurred at SF Recycling & Disposal facilities. However, no safety incidents were reported during the data collection period.

Norcal's Facilities

In March 2002, Norcal officially opened a permanent LNG fueling station at SF Recycling & Disposal (Figure 3). From late 2001 to when the new station opened, the trucks were fueled from a temporary LNG fueling station. The permanent station, designed and built by NexGen Fueling for Clean Energy (formerly ENRG), stores 15,000 gallons of LNG. Clean Energy owns and services the LNG station and leases the equipment to Norcal. Approximately 10,000 gallons of LNG are trucked in from Wyoming once per week. During the evaluation period, the LNG trucks consumed 30,000-40,000 gallons of LNG per month. At the time of this report, there were no regular users of the LNG fueling station other than SF Recycling & Disposal.

PIX 11609

Figure 3. LNG Fueling Station at SF Recycling & Disposal

Efforts are underway to provide alternative sources of LNG for the Bay Area to ensure more reliable access to LNG and to reduce trucking costs. The timeframe for obtaining alternative sources is currently unknown. Options for LNG access in California range from a full production LNG plant to small-scale liquefaction to import terminal access for LNG in locations such as Long Beach.

Diesel fuel is stored and dispensed at SF Recycling & Disposal for all Norcal companies in the San Francisco area. Figure 4 shows diesel storage, and Figure 5 shows the diesel fueling islands. The diesel is delivered in 8,000-gallon increments four to five times per week (typically 150,000 gallons per month).

Norcal's trucks typically are fueled at the fueling island, moved to a nearby location to be cleaned, then driven out. The transfer trucks are then loaded on a scale to 80,000 lb before leaving the facility. Each diesel fueling event is tracked electronically at the dispenser and through fuel cards assigned to each truck.

Figure 6 shows the maintenance facility at SF Recycling & Disposal. Equipment was added for sensing natural gas and increasing ventilation in the maintenance facility for safe indoor operation of LNG trucks. These upgrades cost about $80,000. The mechanics and operators received training for dispensing LNG fuel at the station and for general safety related to LNG trucks. The mechanics received more detailed instruction from two on-site CWI technicians at the start of the LNG truck operations and as the operations progressed.

PIX 11626

Figure 4. Diesel and Gasoline On-Site Storage at SF Recycling & Disposal

PIX 11611

Figure 5. Diesel Fueling Islands at SF Recycling & Disposal

PIX 11619

Figure 6. Maintenance Facility at SF Recycling & Disposal

Project Start-Up at Norcal

Norcal's LNG trucks were started into service over a 5-month period from August through December 2001. These trucks were purchased new with diesel ISX engines and upfitted to LNG operation. The trucks did not operate exclusively on diesel before being converted to LNG operation except for being driven from the dealership for delivery to SF Recycling & Disposal. Drivers liked the LNG trucks from the beginning. One of the main factors may have been the higher maximum horsepower and peak torque compared with the older diesel trucks used in the rest of the waste transfer truck fleet.

PIX 13169

To monitor the LNG trucks and keep them operating well, CWI stationed two technicians at SF Recycling & Disposal. The CWI technicians resolved issues with the engine and fuel system that could be addressed on site and continue to work on location in San Francisco.

It took time before the LNG trucks were used to their full potential. A typical transfer truck operates for two 10-hour shifts per day 5 days per week and one 10-hour shift on Saturday. There was a delay before the LNG trucks were used for the second shift because of a lack of training and familiarization provided to the second shift drivers and supervisors. Over time, the supervisors and drivers on the second shift were encouraged to start using the LNG trucks in normal operations. The smaller, more labor-intensive temporary LNG station in use before March 2002 also slowed full implementation of the LNG trucks. Starting around July 2002, the LNG trucks were in standard operations similar to those of the fleet's diesel trucks.

The biggest operating problem for the LNG trucks was foreign matter getting into the fuel system, which damaged the seals and caused the high-pressure fuel pumps to fail prematurely. This problem was attributed to some LNG fuel system components not being cleaned well enough initially. Some foreign matter was attributed to the LNG fuel, and a fine particle size filter was eventually added to the LNG fueling station to reduce the likelihood of debris getting into the fuel systems. The problem has been reduced significantly but still causes failures.

Evaluation Results

Table 3 shows the start date and evaluation periods for trucks used in the evaluation. In addition to results from the evaluation periods, this report presents some life-to-date results for the LNG trucks. No maintenance data were collected for the older diesel trucks. The LNG trucks and new diesel trucks were at the beginning of their useful lives, whereas the older diesel trucks were near the end of their useful lives during the evaluation.

General Duty Cycle Description

The LNG trucks are used on standard transfer truck routes from the SF Recycling & Disposal facility to the landfill (Figure 7). The round trip is approximately 120 miles.

The transfer trucks make as many as six trips per day (during two shifts) to the landfill, 5–6 days per week. When the LNG trucks are in full operation, each is expected to

Table 3. Evaluation Periods Used for This Evaluation

Group	Truck	Start of Operation	Use Data Period	Fuel Data Period	Maintenance Data Period	Odometer as of 7/31/03 (mi)
LNG	16106	9/26/01	8/02-7/03	8/02-7/03	8/02-7/03	160,570
	16107	9/25/01	8/02-7/03	8/02-7/03	8/02-7/03	163,882
	16108	8/1/01	8/02-7/03	8/02-7/03	8/02-7/03	183,225
	16109	9/3/01	8/02-7/03	8/02-7/03	8/02-7/03	202,376
	16110	8/24/01	8/02-7/03	8/02-7/03	8/02-7/03	177,810
	16113	10/31/01	8/02-7/03	8/02-7/03	8/02-7/03	163,646
	16114	10/24/01	8/02-7/03	8/02-7/03	8/02-7/03	168,700
	16115	10/26/01	8/02-7/03	8/02-7/03	8/02-7/03	188,271
	16116	12/19/01	8/02-7/03	8/02-7/03	8/02-7/03	129,542
	16117	10/31/01	8/02-7/03	8/02-7/03	8/02-7/03	123,889
	16118	12/12/01	8/02-7/03	8/02-7/03	8/02-7/03	165,570
	16121	12/19/01	8/02-7/03	8/02-7/03	8/02-7/03	137,868
New Diesel	16125	10/30/02	10/02-7/03	10/02-7/03	10/02-7/03	107,824
	16126	11/7/02	11/02-7/03	11/02-7/03	11/02-7/03	107,209
	16127	12/26/02	12/02-7/03	12/02-7/03	12/02-7/03	70,690
	16128	12/26/02	12/02-7/03	12/02-7/03	12/02-7/03	64,532
	16129	2/13/03	2/03-7/03	2/03-7/03	2/03-7/03	61,386
	16130	2/19/03	2/03-7/03	2/03-7/03	2/03-7/03	53,615
	16133	4/22/03	5/03-7/03	5/03-7/03	5/03-7/03	20,374
Old Diesel	16081	N/A	9/02-7/03	9/02-7/03	N/A	547,281
	16095	N/A	9/02-7/03	9/02-7/03	N/A	474,603
	16096	N/A	9/02-7/03	9/02-7/03	N/A	474,923
	16097	N/A	9/02-7/03	9/02-7/03	N/A	477,960
	16098	N/A	9/02-7/03	9/02-7/03	N/A	495,362

Figure 7. Map of SF Recycling & Disposal Facility (San Francisco) and Landfill (Livermore)

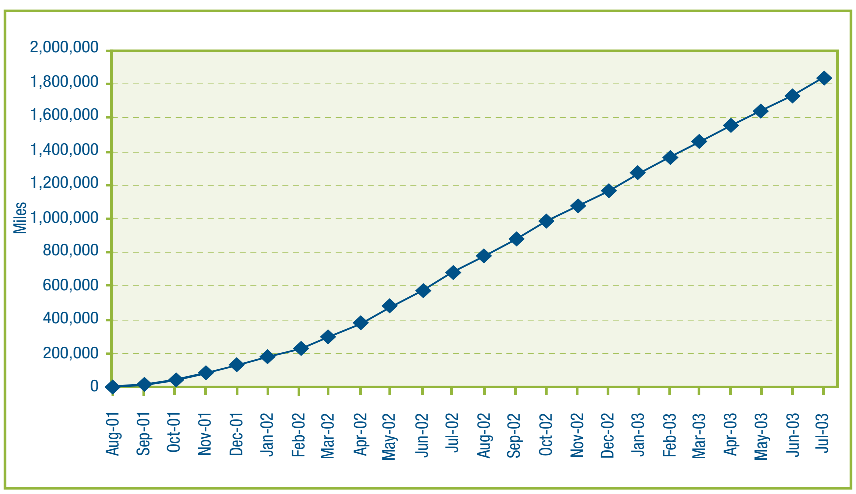


Figure 8. Total Mileage Accumulation for the LNG Trucks

drive approximately 10,000 miles per month (120,000 miles per year). Each is loaded at SF Recycling & Disposal to the legal weight limit of 80,000 lb per trip.

The LNG truck (tractor) weighs nearly 1,000 lb more than the diesel truck, which reduces the load it can carry. Most of the driving is on the highway at an average speed of 37–47 mph, depending on traffic and time of day. All the transfer trucks are electronically limited to a maximum speed of 55 mph.

LNG and Diesel Truck Use

Figure 8 shows the mileage accumulation for the LNG trucks from the start of operation through the end of July 2003. Mileage accumulated slowly in 2001 and picked up in May 2002 as the trucks began to be used on both shifts. Total mileage accumulation through July 2003 was more than 1.8 million miles and through December 2003 was projected to be 2.3 million miles (approximately 100,000 miles per month).

Figure 9 shows the running average monthly mileage per truck for the LNG trucks and the combined old and new diesel trucks. The diesel trucks were combined to represent the entire diesel fleet. The new diesel trucks were used at a higher rate than the older ones because the older diesel trucks have higher operating costs. The running average monthly mileage per truck for the combined diesel trucks was 9% higher than for the LNG trucks, which indicates that the LNG trucks were used at a rate only slightly lower than that of the diesel fleet. The LNG trucks had downtime for maintenance and other issues as described later but, overall, were used at a high rate.

Figure 10 is another measure of truck use at SF Recycling & Disposal. Each truck has a theoretical maximum planned use based on the number of driver shifts used for each truck—10 per week, with another optional shift on Saturday. A truck may not have been used if it was down for maintenance, the driver was not working, or the truck was not needed because of a lack of material to be transported. This analysis was applied to all the trucks, so the comparison gives some indication of differences in use between the groups.

Figure 10 shows that the LNG trucks had significantly lower use around December 2002, and at the same time the diesel trucks were used more. The LNG trucks had a problem with the onboard LNG storage tanks losing vacuum, which caused the LNG pressure inside the tank to increase. This made fueling difficult and caused the LNG tanks to vent natural gas. A solution to the problem was implemented, and LNG truck use returned to normal as shown in the figure.

Fuel Economy and Cost

Tables 4 and 5 and Figure 11 show fuel consumption and fuel economy for the LNG and diesel trucks. The three groups of trucks had the following average fuel economies:

- LNG trucks—4.3 miles per diesel gallon equivalent (mi/DGE)
- New diesel trucks—4.8 mi/DGE
- Old diesel trucks—5.0 mi/DGE.

All three groups operated on the same routes and duty cycles for the entire evaluation period. The old diesel truck group had the highest fuel economy (6% higher than the new diesel group). This was due to differences in the engines. The old diesel trucks have a smaller engine than the new trucks—the N14 engine is 14 L and the ISX is 14.9 L. The old diesel trucks are set to a lower maximum horsepower than the new diesel trucks, and the new diesel trucks have an engine equipped with cooled EGR for emission control.

The LNG trucks consumed LNG and diesel—diesel made up 6.6% of the average energy equivalent consumption during the evaluation period. Fuel economy and percent diesel used were calculated based on the energy content of the fuels related to diesel (see sidebar, page 15). The LNG trucks had an energy equivalent fuel economy 10.5% lower than the new diesel trucks. This is a much better result than seen in previous studies of spark-ignition LNG trucks, which showed a fuel economy penalty of 27%–37% for LNG trucks compared with diesel trucks operating in a similar duty cycle*.

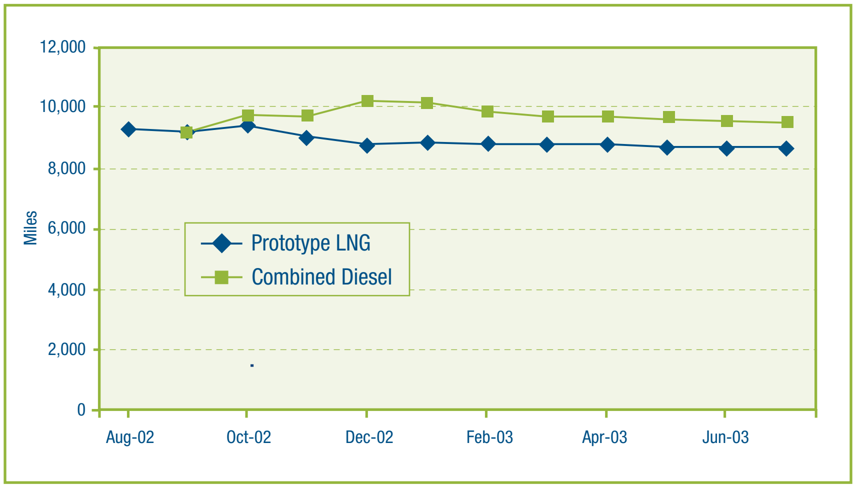


Figure 9. Running Average Monthly Mileage Per Truck

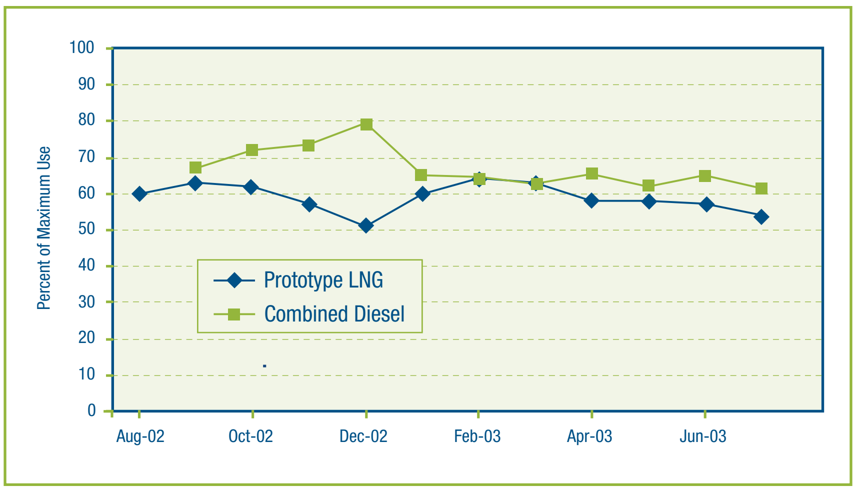


Figure 10. Use of Trucks Compared to Theoretical Maximum Planned Use

* *Raley's LNG Truck Fleet Final Results*, 2000, NREL/BR-540-27678: *Waste Management's LNG Truck Fleet Final Results*, 2001, NREL/BR-540-29073. Visit **www.eere.energy.gov/cleancities/afdc** to obtain these publications.

Table 4. Fuel Consumption and Fuel Economy for LNG Trucks (August 2002-July 2003)

Truck	Mileage Used	LNG (std gal)	Diesel (gal)	Fuel Economy (mi/DGE)	Percent Diesel Used
16106	85,126	32,435	1,503	4.1	6.8
16107	81,725	30,482	1,311	4.2	6.0
16108	104,400	37,883	1,577	4.3	6.4
16109	101,438	37,484	1,658	4.2	6.5
16110	100,979	39,899	1,701	4.0	6.5
16113	103,444	37,018	1,636	4.4	6.7
16114	110,851	41,069	1,782	4.2	6.6
16115	121,848	43,415	2,000	4.4	7.0
16116	79,066	29,211	1,374	4.2	7.1
16117	87,224	31,273	1,321	4.4	6.6
16118	119,469	43,036	1,873	4.3	6.7
16121	98,917	35,563	1,647	4.3	7.1
LNG	**1,115,421**	**409,555**	**18,009**	**4.3**	**6.6**

Table 5. Fuel Consumption and Fuel Economy for Old and New Diesel Trucks (September 2002-July 2003)

Truck	Mileage Used	Diesel (gal)	Fuel Economy (mi/DGE)
16125	107,310	22,239	4.8
16126	105,777	22,066	4.8
16127	70,264	14,686	4.8
16128	64,375	14,393	4.5
16129	59,101	12,294	4.8
16130	51,242	10,577	4.8
16133	20,286	4,400	4.6
New Diesel	**478,355**	**100,654**	**4.8**
16081	95,013	18,511	5.1
16095	98,338	19,353	5.1
16096	99,890	19,704	5.1
16097	83,984	17,832	4.7
16098	106,144	20,818	5.1
Old Diesel	**483,369**	**96,218**	**5.0**

In this evaluation, the LNG cost was high owing to the delivery cost from Wyoming to the Bay Area. During the evaluation, LNG cost an average of $1.18/gal, which translates into $2.27/DGE with road use taxes included. During the same period, diesel at SF Recycling & Disposal cost an average of $1.45/gal with road use taxes included. For LNG operation to make economic sense in the long run, the LNG must be available from nearby sources. Work is being done to develop LNG production and increase availability near the Bay Area.

Engine Oil Consumption

The LNG trucks use the same engine oil as the new diesel trucks. Engine oil consumption for the LNG trucks was 9% higher than for the new diesel trucks (oil consumption was not measured in the old diesel trucks). The oil consumption was small, and the difference between the LNG and new diesel trucks is not considered significant:

- LNG trucks—0.35 quarts per 1,000 miles (2,857 miles per quart)
- New diesel trucks—0.32 quarts per 1,000 miles (3,125 miles per quart).

Maintenance Costs and Issues

Maintenance data were collected from SF Recycling & Disposal for each LNG and new diesel truck from the beginning of operation. All available maintenance work orders and parts information were collected for the evaluation trucks. The maintenance cost discussion presented here focuses on the evaluation period (August 2002 through July 2003) unless stated otherwise. Labor costs were held constant at $50 per hour.

Nearly all LNG fuel- and engine-related parts replacements (injectors, fuel conditioning regulators, LNG pumps, high-pressure diesel pumps, etc.) were provided by CWI at no cost; however, in most cases, the SF Recycling & Disposal mechanics did the work. The maintenance cost data therefore include the labor hours of the mechanics from the site but not the cost of parts from CWI. This mechanic labor cost also includes time spent for training.

Because of the random nature of accidents, maintenance actions for tires, and part costs

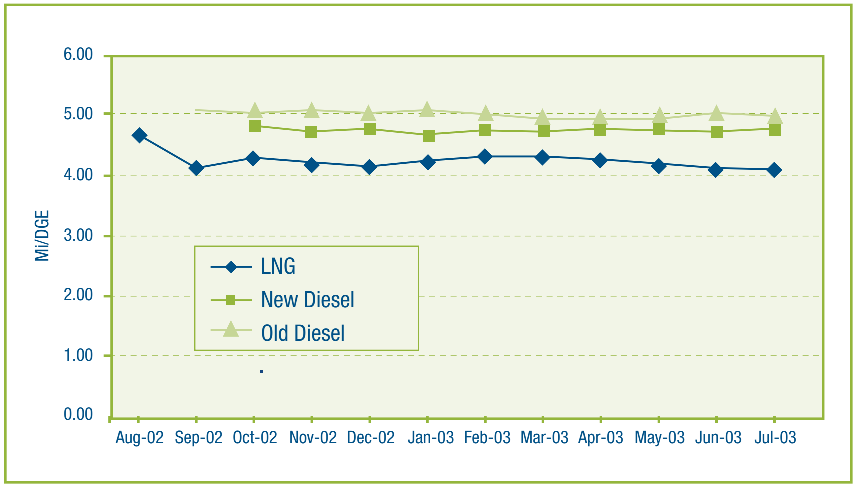
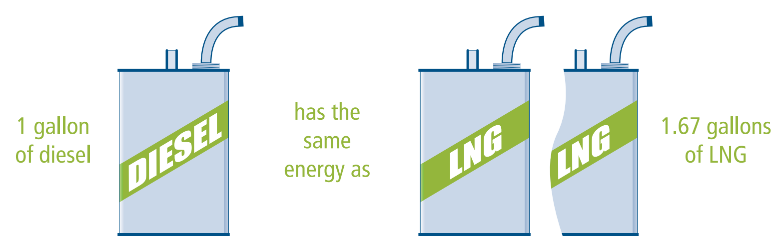


Figure 11. Fuel Economy by Group (August 2002-July 2003)

Calculating Energy Equivalent Fuel Economy for LNG and Diesel

LNG is measured in mass units (pounds) when it is delivered to the truck's storage system. However, the dispenser at the LNG station electronically converts the measurement from pounds to gallons and displays gallons of LNG dispensed at a specific pressure. The next step in calculating fuel economy is to adjust the LNG gallons to atmospheric pressure rather than the pressure dispensed into the truck. This is called a standard LNG gallon.

Because LNG contains less energy per gallon than diesel, comparing simple miles per gallon of LNG and diesel trucks would not accurately compare their true fuel efficiencies. Diesel gallon equivalents (DGEs) are commonly used to solve this problem. A DGE is the quantity of LNG (or any other fuel) that contains the same energy as a gallon of diesel. Because 1.67 gallons of LNG contain the same energy as 1 gallon of diesel, 1.67 gallons of LNG equal 1 DGE.



The fuel economy of the LNG trucks was calculated based on energy content of the LNG fuel plus energy content of the diesel used, giving the following final fuel economy calculation with units of miles per DGE:
Fuel Economy = Miles traveled/(LNG std gal/1.67 + diesel gal)

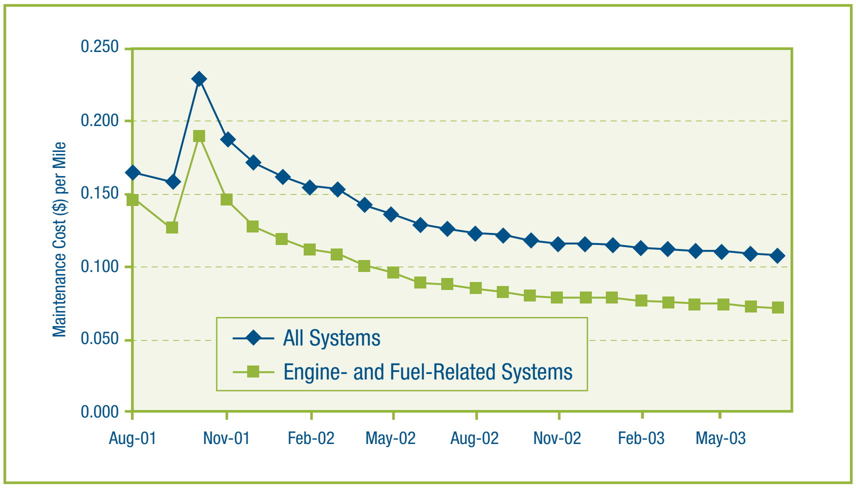


Figure 12. Running Average Total Maintenance Costs and Engine/Fuel-Related Systems for LNG Trucks

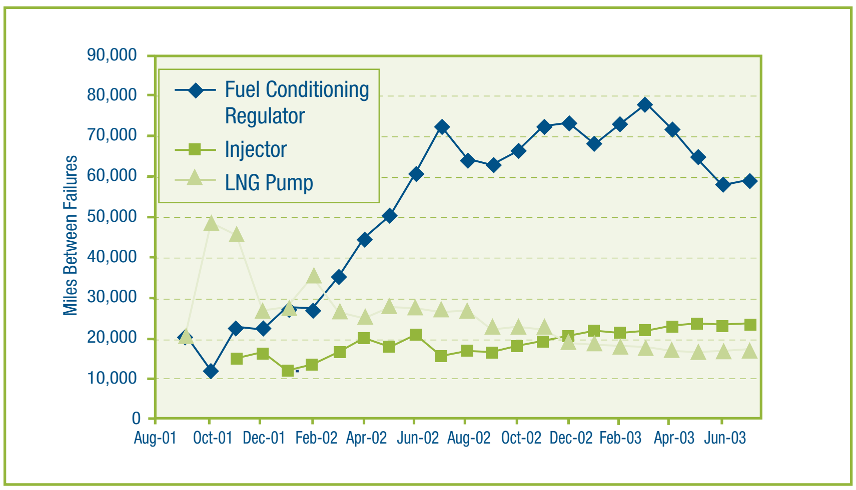


Figure 13. Running Average Miles Between Failures for LNG Components

for wheels, all maintenance actions marked as such were removed for this discussion. There were two significant accidents during the data collection period, both involving LNG trucks. The first occurred with Truck 16113 on April 3, 2002, which is outside the evaluation period. This was a small fire caused by a diesel fuel hose rubbing on a battery cable (cost: $1,358.30 parts and 30.5 labor hours). This incident was caused by an issue related to integration of the LNG systems. The second occurred on February 26, 2003 and involved Truck 16117, which ran off the road and sustained significant structural damage to the frame and rear end (cost: $123.63 parts and 76 labor hours for repairing damage, $0.003/mi removed from the evaluation period); this incident was not caused by an engine or fuel system failure.

Because the transfer trucks are operated at the landfill, the tires and wheels are randomly damaged by debris. For the evaluation period, tire and wheel costs were removed for the LNG trucks (cost: $34,425.05 parts and 208.5 labor hours, $0.036/mi, which represents 27% of the total maintenance costs). Tire and wheel costs were also removed for the new diesel truck group (cost: $4,948.15 parts and 68.75 labor hours, $0.017/mi, which represents 29% of the total maintenance costs).

Table 6 shows the remaining maintenance costs (minus accidents, tires, and wheel repairs) for the LNG trucks; Table 7 shows the same for the new diesel trucks. Not surprisingly, the total maintenance costs for the LNG trucks were 2.3 times higher than for the new diesel trucks. Any time a major new technology is introduced, there are significant maintenance costs. Furthermore, the LNG trucks were older and had higher mileage, factors that typically increase maintenance requirements. The objective of this discussion is to look for indications of improvement and barriers to maturing this technology.

Figure 12 shows running average maintenance costs for all LNG truck maintenance and for only engine- and fuel-related systems. The engine- and fuel-related systems include non-lighting electrical, air intake, cooling, exhaust, fuel, engine, and hydraulic systems. The maintenance costs for the engine- and fuel-related systems decreased significantly

Table 6. Adjusted Maintenance Costs for LNG Trucks (August 2002-July 2003)				
Truck	Mileage Used*	Parts ($)	Labor Hours	Cost ($/mi)
16106	90,226	880.00	190.00	0.115
16107	91,496	979.78	167.75	0.102
16108	105,970	1,210.15	194.25	0.103
16109	107,979	1,349.25	184.25	0.098
16110	102,827	1,881.97	211.75	0.121
16113	105,991	1,358.72	189.00	0.102
16114	113,060	1,618.25	178.25	0.093
16115	124,543	1,414.10	148.50	0.071
16116	81,818	1,155.58	168.75	0.117
16117	87,585	1,124.23	171.75	0.111
16118	121,692	1,311.82	122.00	0.061
16121	100,441	1,436.71	139.25	0.084
Total	**1,233,628**	**15,720.56**	**2,065.50**	**0.096**

* Mileage accumulated during the data period.

Table 7. Adjusted Maintenance Costs for New Diesel Trucks (October 2002-July 2003)				
Truck	Mileage Used*	Parts ($)	Labor Hours	Cost ($/mi)
16125	107,310	679.71	78.75	0.043
16126	106,810	526.39	51.00	0.029
16127	70,631	382.68	50.00	0.041
16128	64,375	217.87	57.00	0.048
16129	59,101	736.96	45.75	0.051
16130	51,704	156.56	17.25	0.020
16133	20,286	106.37	21.25	0.058
Total	**480,217**	**2,915.77**	**345.00**	**0.042**

* Mileage accumulated during the data period.

since the LNG truck fleet began operation. This indicates that maintenance issues are decreasing and reliability is increasing.

Figure 13 shows running average miles between failures of three major LNG truck propulsion systems: the LNG pump, fuel conditioning regulator, and special HPDI injectors. Problems with the LNG pump were caused almost exclusively by debris in the fuel. The LNG pump is extremely sensitive to debris in the fuel because of the high pressures used for fuel injection. The debris damages the LNG pump seals. The solution was to add more filtration to the fueling station dispenser and on the trucks. Currently, the LNG pumps are being rebuilt and reused in the LNG trucks.

The fuel conditioning regulator is a part of the high-pressure diesel fuel side of the fueling system. It is a general indicator of the diesel fuel system maintenance issues, and it had some early problems. Current data show that the failure rate is 60,000–70,000 miles between failures, which translates into changes of the fuel conditioning regulator twice per year based on current truck use at SF Recycling & Disposal. Other significant diesel fuel system problems have been experienced with the high-pressure diesel pump and drive belt. A diesel pump and drive belt change (with a better integrated solution) is planned for the LNG trucks.

Since start of operation, the average failure rate was one HPDI injector every 24,000

LNG Tank Vacuum Problem

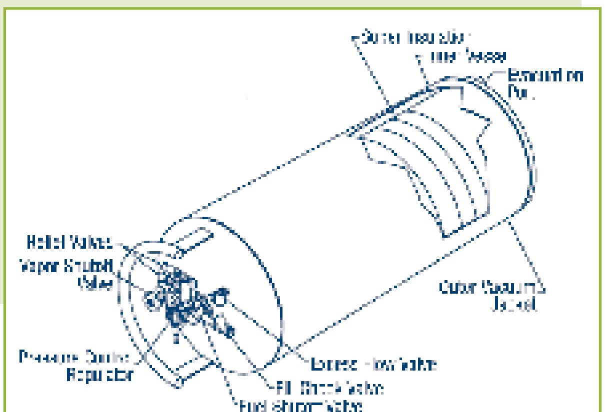
A typical stainless steel LNG tank has an inner and an outer fuel tank shell. The manufacturer places insulation material between these two shells to control and maintain a vacuum. This tank design has worked well for LNG tanks smaller than 80 gal.

Most of Norcal's LNG trucks have had an issue with their LNG tank vacuum. This was originally thought to be a manufacturing quality control problem. NexGen Fueling (the tank manufacturer) determined that the vacuum was being degraded by hydrogen off-gassing from the tank's stainless steel. The hydrogen is extremely difficult to remove when the vacuum is pulled down (i.e., when the air is removed from the vacuum space) after manufacturing. More hydrogen off-gasses from the stainless steel after the vacuum is first pulled and degrades that vacuum over time. Several other truck fleets experienced this problem at about the same time as Norcal's trucks.

In 2000, NexGen Fueling started to manufacture larger LNG tanks (100–150 gal) for trucking applications. These tanks had larger stainless steel surface areas adjacent to the vacuum space, which provided more hydrogen off-gassing to the vacuum space than expected. This extra hydrogen was the leading cause of the vacuum loss.

Loss of vacuum for the LNG tanks allows more heat leakage into the LNG storage area. This heat leakage causes the LNG to boil off and increase pressure in the tank. At high pressure, the LNG tank is designed to vent to protect it from damage. When fueling the LNG tank, this high pressure can make the LNG dispenser shut off before the tank is full because the dispenser is monitoring the back-pressure to make sure that the tank is not overfilled. The resulting lack of fuel in the tank has caused problems with road calls due to the tank being unexpectedly empty.

The solution for this problem has been determined to be periodically pulling the vacuum down with a special pump. NexGen Fueling suggested that fleet operators monitor the tanks and pull the vacuum down only when the tank has lost a significant amount of vacuum because the insulation in the vacuum space could be damaged by the procedure. If the insulation is damaged, the LNG tank must be replaced. The vacuum is going "soft" when the tank begins to sweat and ice starts to collect. With a soft vacuum, LNG use increases at 10%–15% per fueling. At the end of this evaluation (July 2003), this problem appeared to be getting better but was not completely resolved.



LNG Tank Schematic (courtesy of NexGen Fueling)

miles. This translates into a set of six injectors being replaced every 132,000 miles or about once per year. This failure rate improved over the evaluation period.

Road Calls

A road call is a truck failure that requires service while the truck is on the road. In some cases, the truck must be towed or driven to the maintenance shop. Sometimes it can be repaired in the field.

Figure 14 shows miles between road calls for the LNG trucks' entire operation period. The best road call rate occurred between December 2001 and December 2002, after which the road call rate increased. One reason for the increase was problems with LNG tank vacuums, which caused the LNG tanks to have high fuel pressure and made fueling difficult. Much of the LNG fuel vented from the tanks instead of being burned in the engines, causing trucks to run out of fuel unexpectedly. There were eight road calls for this problem during December 2002. A resolution to the problem was identified (see sidebar, page 18), and the road call rate began to improve slowly after December 2002 as the resolution began to be implemented.

Table 8 summarizes road calls by cause for the LNG trucks' entire operation period and for the evaluation period. Nearly 90% of the road calls were for problems with the engine- and fuel-related systems (non-lighting electrical, air intake, cooling, exhaust, fuel, engine, and hydraulics). The three top causes for road calls were pump failure, the truck running out of LNG, and problems with the propulsion system's electrical wiring (typically wiring coming loose).

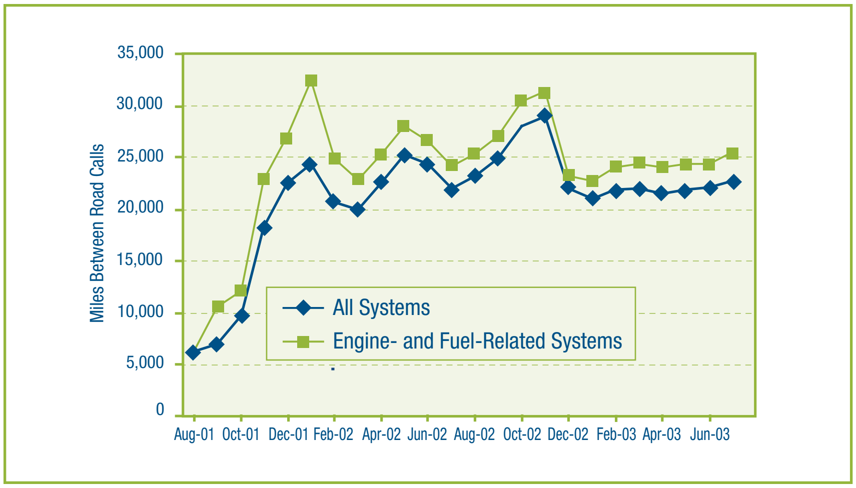


Figure 14. Miles Between Road Calls for the LNG Trucks

Table 8. Summary of LNG Truck Road Calls by Cause

System Causing Road Call	Since Inception	Percent of Total Road Calls	During Evaluation Period	Percent of Total Road Calls
Engine/Fuel-Related Systems	**76**	**88**	**47**	**89**
LNG Pump	23	27	14	26
Engine/Fuel – Electrical/Wires	17	20	7	13
Out of LNG	14	16	10	19
Diesel Fuel System	9	11	5	9
Injectors	4	5	3	6
LNG Tank	2	2	2	4
Cooling System	2	2	1	2
Exhaust Leak	2	2	2	4
Starter	2	2	2	4
Engine Oil Leak	1	1	1	2
Other Systems	**10**	**12**	**6**	**11**
Air System/Brakes	6	8	4	7
Mirror	1	1	0	0
Transmission	1	1	0	0
Accident	1	1	1	2
Rear Axle	1	1	1	2
Total Road Calls	**86**	**100**	**53**	**100**

Summary

Norcal and CWI tested prototype LNG trucks to learn more about the maturity of the Westport-Cycle based fueling system on the Cummins ISX engine platform. The objective was to determine how close the ISXG is to commercialization and what design changes and integration work might be required to bring the technology to a commercial level of reliability. Many successes and a few disappointments resulted from this evaluation:

- Drivers reported that the performance of the LNG trucks was as good as or better than that of the diesel trucks.
- The LNG trucks were operated more than 1.8 million miles through July 2003 and were projected to operate 2.3 million miles through December 2003. The LNG trucks have been used at a rate of 100,000 miles per month. This high use rate for the LNG trucks indicates improving reliability.
- The LNG trucks were used nearly as much as the diesel trucks in the same operation, with average monthly mileage 9% lower during the evaluation period. This is much better than previous results from other LNG truck operations, in which other LNG trucks typically were used 25% less than diesel trucks*.
- The energy equivalent fuel economy was 10.5% lower for the prototype LNG trucks compared with the newest diesel trucks. This is much better than results from previous studies of spark-ignition, heavy-duty natural gas trucks, which had equivalent fuel economies 27%–37% lower than diesel trucks over the same duty cycle*.
- Maintenance costs for the prototype LNG trucks were 2.3 times higher per mile than for the newest commercial diesel trucks. This was expected because the LNG engine technology is in the prototype stage. For CWI, one objective of this project was to study ways to enhance reliability of this new potential product. The components and systems with maintenance issues were the LNG pump, high-pressure diesel fuel system, and HPDI injectors. CWI continues to plan better integration strategies for these and other related components.
- Nearly 90% of the road calls for the LNG trucks were due to the engine- and fuel-related systems (non-lighting electrical, air intake, cooling, exhaust, fuel, engine, and hydraulic systems). The mileage between road calls began to improve after an issue with the onboard LNG tanks losing vacuum began to be resolved.
- Use of "clean" LNG was a major concern. Contaminants in LNG pose a threat to high-pressure LNG pumps and onboard injectors. CWI implemented additional filtration on the trucks and worked with Clean Energy to implement additional filtration at the fueling station. CWI plans to make changes to the LNG pump and onboard fuel system to alleviate some of the sensitivity to contaminants.
- The high cost of LNG used in the evaluation resulted mainly from delivery costs from Wyoming to San Francisco. Producing LNG nearby or constructing an import terminal would alleviate much of this cost. Energy suppliers are exploring these options.

* *Raley's LNG Truck Fleet Final Results*, 2000, NREL/BR-540-27678; *Waste Management's LNG Truck Fleet Final Results*, 2001, NREL/BR-540-29073. Visit **www.eere.energy.gov/cleancities/afdc** to obtain these publications.

What's Next for the ISXG Engine

Originally, CWI and Norcal planned to upfit the nine new 2003 ISX diesel trucks with a new version of the LNG fuel system and engine. These trucks were to be early commercial versions of this propulsion system. However, CWI recently decided to delay the commercial release of the ISXG engine owing to market conditions.

In October 2003, CWI announced that the ISXG engine (using the cooled EGR diesel engine platform) was certified in California to the optional low-NO_x emission standard of 1.5 g/bhp-hr (test results for this engine were 1.2 g/bhp-hr), and that 0.6 g/bhp-hr NO_x (which is extremely low for a heavy-duty engine) had been reached on the engine dynamometer.

CWI intends to reduce the ISXG's NO_x emissions to 0.2 g/bhp-hr and hopes to introduce it commercially in the 2007-2008 timeframe. This will require increasing the injection pressure, using more EGR, and increasing control of air handling in the engine. Heavy-duty diesel and natural gas engines are not required to be at this level until 2010 (Table 9). The next round of demonstrations for the LNG truck engine is expected in 2005 and may include a market development demonstration of the current 1.2 g/bhp-hr NO_x engine and a technology demonstration of the 0.2 g/bhp-hr level.

Future ISXG engines also will include an improved LNG pump and more robust HPDI injectors. The improved pump is expected to reduce complications due to debris in the fuel. The more robust HPDI injectors are expected to reduce the rate of injector failure significantly. New hardware and calibrations will improve efficiency, and a higher-power (450 hp) engine rating may be available. CWI also has significant integration and packaging engineering work planned for the truck platform to reduce maintenance costs and increase reliability.

Norcal currently has no plans to purchase additional LNG trucks. However, the LNG trucks at SF Recycling & Disposal are currently operating in the configuration described in this report. Some additions and changes may be made to the high-pressure fuel systems, and CWI will continue to support Norcal's LNG trucks.

Table 9. EPA Heavy-Duty Highway Engine 2007/2010 Emission Standards

	Emission Standard (g/bhp-hr)	Percent of Engine Sales, Model Year 2007-2009	Percent of Engine Sales, Model Year 2010
PM	0.01	100%	100%
NO_x	0.20	50%	100%
NMHC	0.14	50%	100%

For a detailed explanation of emission standards visit **www.epa.gov**.

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Acronyms and Abbreviations

AVTA	Advanced Vehicle Testing Activity
CO	Carbon monoxide
CWI	Cummins Westport, Inc.
DGE	Diesel gallon equivalent
DOE	U.S. Department of Energy
EGR	Exhaust gas recirculation
gal	Gallons
g/bhp-hr	Grams per brake horsepower hour
GCWR	Gross combination weight rating
GVWR	Gross vehicle weight rating
h	Hours
HC	Hydrocarbons
hp	Horsepower
HPDI	High-pressure direct injection
ISX	Cummins diesel engine platform evaluated in this report
ISXG	CWI LNG engine platform—the prototype version is evaluated in this report
lb-ft	Pound-foot
L	Liter
LNG	Liquefied natural gas
mi	Miles
NO_x	Oxides of nitrogen
NMHC	Nonmethane hydrocarbons
PM	Particulate matter
psi	Pounds per square inch
rpm	Rotations per minute
THC	Total hydrocarbons
Westport-Cycle	The HPDI operation of LNG and diesel

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Appendix: Fleet Summary Statistics

**Norcal Waste/SF Recycling & Disposal, Inc. (San Francisco, CA)
Fleet Summary Statistics**

—Vehicles Included in Evaluation

Fleet Operations and Economics	LNG 16106-18; 21	New Diesel 16125-30; 33	Old Diesel
Number of Vehicles	12	7	5
Period Used for Fuel and Oil Op Analysis	8/02-7/03	10/02-7/03	9/02-7/03
Total Number of Months in Period	12	10	11
Fuel and Oil Analysis Base Fleet Mileage	1,115,421	478,355	483,369
Period Used for Maintenance Op Analysis	8/02-7/03	10/02-7/03	N/A
Total Number of Months in Period	12	10	N/A
Maintenance Analysis Base Fleet Mileage	1,233,628	480,217	N/A
Average Monthly Mileage per Vehicle	8,688	10,381	8,835
Fleet LNG Use (gal)	409,555	0	0
Fleet Diesel Use (gal)	18,009	100,654	96,218
Representative Fleet Fuel Economy (mi/DGE)*	4.24	4.75	5.02
Revised Fleet Fuel Economy (mi/DGE)*	4.25	4.75	5.02
Diesel Used (%, based on energy)*	6.84	100.00	100.00
Revised Diesel Used (%, based on energy)*	6.64	100.00	100.00
Average LNG Cost as Reported, with Tax ($/gal)	1.18	N/A	N/A
Average LNG Cost per Energy Equivalent ($/DGE)*	2.27	N/A	N/A
Diesel Cost, with Tax ($/gal)	1.45	1.45	1.45
Fuel Cost per Mile ($)	0.523	0.305	0.289
Number of Make-Up Oil Quarts per Mile	0.0003	0.0003	N/A
Oil Cost per Quart ($)	0.88	0.88	N/A
Oil Cost per Mile ($)	0.0003	0.0003	N/A
Total Scheduled Repair Cost per Mile ($)	0.023	0.015	N/A
Total Unscheduled Repair Cost per Mile ($)	0.110	0.045	N/A
Total Maintenance Cost per Mile ($)	0.133	0.059	N/A
Total Operating Cost per Mile ($)	**0.656**	**0.365**	**N/A**

* See sidebar on page 15 for energy equivalent fuel economy calculation.

Maintenance Costs	LNG 16106-18; 21	New Diesel 16125-30; 33
Fleet Mileage	1,233,628	480,217
Total Parts Cost ($)	50,145.61	7,863.92
Total Labor Hours (h)	2274.0	413.8
Average Labor Cost ($) (@ $50.00 per hour)	113,700.00	20,687.50
Total Maintenance Cost ($)	163,845.61	28,551.42
Total Maintenance Cost per Truck ($)	13,653.80	4,078.77
Total Maintenance Cost per Mile ($)	**0.133**	**0.059**

Breakdown of Maintenance Costs by Vehicle System		
Total Engine/Fuel-Related Systems (ATA VMRS 30, 31, 32, 33, 41, 42, 43, 44, 45, 65)		
	LNG 16106-18; 21	**New Diesel 16125-30; 33**
Parts Cost ($)	9,621.65	2,098.86
Labor Hours	1343.3	112.3
Average Labor Cost ($)	67,162.50	5,612.50
Total Cost for System ($)	76,784.15	7,711.36
Total Cost for System per Truck ($)	6,398.68	1,101.62
Total Cost for System per Mile ($)	**0.0622**	**0.0161**
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost ($)	194.10	98.84
Labor Hours	39.3	19.3
Average Labor Cost ($)	1,962.50	962.50
Total Cost for System ($)	2,156.60	1,061.34
Total Cost for System per Truck ($)	179.72	151.62
Total Cost for System per Mile ($)	**0.0017**	**0.0022**
Fuel System Repairs (ATA VMRS 44)		
Parts Cost ($)	690.04	119.70
Labor Hours	893.3	11.0
Average Labor Cost ($)	44,662.50	550.00
Total Cost for System ($)	45,352.54	669.70
Total Cost for System per Truck ($)	3,779.38	95.67
Total Cost for System per Mile ($)	**0.0368**	**0.0014**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost ($)	4,199.35	1,304.11
Labor Hours	222.5	54.3
Average Labor Cost ($)	11,125.00	2,712.50
Total Cost for System ($)	15,324.35	4,016.61
Total Cost for System per Truck ($)	1,277.03	573.80
Total Cost for System per Mile ($)	**0.0124**	**0.0084**

Breakdown of Maintenance Costs by Vehicle System (continued)	LNG 16106-18; 21	New Diesel 16125-30; 33
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts Cost ($)	2,042.04	0.00
Labor Hours	110.8	6.3
Average Labor Cost ($)	5,537.50	312.50
Total Cost for System ($)	7,579.54	312.50
Total Cost for System per Truck ($)	631.63	44.64
Total Cost for System per Mile ($)	**0.0061**	**0.0007**
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost ($)	1,677.26	387.06
Labor Hours	0.3	1.3
Average Labor Cost ($)	12.50	62.50
Total Cost for System ($)	1,689.76	449.56
Total Cost for System per Truck ($)	140.81	64.22
Total Cost for System per Mile ($)	**0.0014**	**0.0009**
Cooling System Repairs (ATA VMRS 42)		
Parts Cost ($)	346.48	187.15
Labor Hours	14.8	20.3
Average Labor Cost ($)	737.50	1,012.50
Total Cost for System ($)	1,083.98	1,199.65
Total Cost for System per Truck ($)	90.33	171.38
Total Cost for System per Mile ($)	**0.0009**	**0.0025**
Hydraulic System Repairs (ATA VMRS 65)		
Parts Cost ($)	472.38	0.00
Labor Hours	62.5	0.0
Average Labor Cost ($)	3,125.00	0.00
Total Cost for System ($)	3,597.38	0.00
Total Cost for System per Truck ($)	299.78	0.00
Total Cost for System per Mile ($)	**0.0029**	**0.0000**
Brake and General Air System Repairs (ATA VMRS 10, 13)		
Parts Cost ($)	1,136.63	55.13
Labor Hours	84.0	30.0
Average Labor Cost ($)	4,200.00	1,500.00
Total Cost for System ($)	5,336.63	1,555.13
Total Cost for System per Truck ($)	444.72	222.16
Total Cost for System per Mile ($)	**0.0043**	**0.0032**

Breakdown of Maintenance Costs by Vehicle System (continued)	LNG 16106-18; 21	New Diesel 16125-30; 33
Transmission and Clutch Repairs (ATA VMRS 23, 26)		
Parts Cost ($)	16.00	0.00
Labor Hours	8.8	6.8
Average Labor Cost ($)	437.50	337.50
Total Cost for System ($)	453.50	337.50
Total Cost for System per Truck ($)	37.79	48.21
Total Cost for System per Mile ($)	**0.0004**	**0.0007**
Inspections Only - no parts replacements (101)		
Parts Cost ($)	0.00	0.00
Labor Hours	377.8	106.3
Average Labor Cost ($)	18,887.50	5,312.50
Total Cost for System ($)	18,887.50	5,312.50
Total Cost for System per Truck ($)	1,573.96	758.93
Total Cost for System per Mile ($)	**0.0153**	**0.0111**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost ($)	2,277.99	278.97
Labor Hours	86.5	42.5
Average Labor Cost ($)	4,325.00	2,125.00
Total Cost for System ($)	6,602.99	2,403.97
Total Cost for System per Truck ($)	550.25	343.42
Total Cost for System per Mile ($)	**0.0054**	**0.0050**
HVAC System Repairs (ATA VMRS 01)		
Parts Cost ($)	65.00	0.00
Labor Hours	4.5	0.8
Average Labor Cost ($)	225.00	37.50
Total Cost for System ($)	290.00	37.50
Total Cost for System per Truck ($)	24.17	5.36
Total Cost for System per Mile ($)	**0.0002**	**0.0001**
Fifth Wheel Repairs (ATA VMRS 59)		
Parts Cost ($)	0.00	0.00
Labor Hours	4.3	1.5
Average Labor Cost ($)	212.50	75.00
Total Cost for System ($)	212.50	75.00
Total Cost for System per Truck ($)	17.71	10.71
Total Cost for System per Mile ($)	**0.0002**	**0.0002**

Breakdown of Maintenance Costs by Vehicle System (continued)	LNG 16106-18; 21	New Diesel 16125-30; 33
Lighting System Repairs (ATA VMRS 34)		
Parts Cost ($)	1,280.02	223.39
Labor Hours	56.5	12.5
Average Labor Cost ($)	2,825.00	625.00
Total Cost for System ($)	4,105.02	848.39
Total Cost for System per Truck ($)	342.09	121.20
Total Cost for System per Mile ($)	**0.0033**	**0.0018**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts Cost ($)	915.22	250.24
Labor Hours	28.3	5.5
Average Labor Cost ($)	1,412.50	275.00
Total Cost for System ($)	2,327.72	525.24
Total Cost for System per Truck ($)	193.98	75.03
Total Cost for System per Mile ($)	**0.0019**	**0.0011**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost ($)	6,971.60	1,886.48
Labor Hours	71.8	27.0
Average Labor Cost ($)	3,587.50	1,350.00
Total Cost for System ($)	10,559.10	3,236.48
Total Cost for System per Truck ($)	879.93	462.35
Total Cost for System per Mile ($)	**0.0086**	**0.0067**
Tire Repairs (ATA VMRS 17)		
Parts Cost ($)	27,861.50	3,072.85
Labor Hours	208.5	68.8
Average Labor Cost ($)	10,425.00	3,437.50
Total Cost for System ($)	38,286.50	6,510.35
Total Cost for System per Truck ($)	3,190.54	930.05
Total Cost for System per Mile ($)	**0.0310**	**0.0136**

Norcal Waste/SF Recycling & Disposal, Inc. (San Francisco, CA)
Fleet Summary Statistics

—Vehicles Excluded from Evaluation

Fleet Operations and Economics	LNG 16119-20	New Diesel 16131-2
Number of Vehicles	2	2
Period Used for Fuel and Oil Op Analysis	8/02-7/03	3/03-7/03
Total Number of Months in Period	12	5
Fuel and Oil Analysis Base Fleet Mileage	46,282	27,386
Period Used for Maintenance Op Analysis	8/02-7/03	3/03-7/03
Total Number of Months in Period	12	5
Maintenance Analysis Base Fleet Mileage	49,104	27,386
Average Monthly Mileage per Vehicle	2,046	3,043
Fleet LNG Use (gal)	17,231	0
Fleet Diesel Use (gal)	1,119	5,202
Representative Fleet Fuel Economy (mi/DGE)*	4.07	5.26
Diesel Used (%, based on energy)*	9.28	100.00
Average LNG Cost as Reported, with Tax ($/gal)	1.18	N/A
Average LNG Cost per Energy Equivalent ($/DGE)*	2.27	N/A
Diesel Cost, with Tax ($/gal)	1.45	1.45
Fuel Cost per Mile ($)	0.541	0.275
Number of Make-Up Oil Quarts per Mile	0.0003	0.0003
Oil Cost per Quart ($)	0.88	0.88
Oil Cost per Mile ($)	0.0003	0.0003
Total Scheduled Repair Cost per Mile ($)	0.088	0.027
Total Unscheduled Repair Cost per Mile ($)	0.195	0.042
Total Maintenance Cost per Mile ($)	0.283	0.069
Total Operating Cost per Mile ($)	**0.825**	**0.345**

* See sidebar on page 15 for energy equivalent fuel economy calculation.

Maintenance Costs	LNG 16119-20	New Diesel 16131-2
Fleet Mileage	49,104	27,386
Total Parts Cost ($)	2,856.49	560.50
Total Labor Hours ($)	221.0	26.8
Average Labor Cost ($) (@ $50.00 per hour)	11,050.00	1,337.50
Total Maintenance Cost ($)	13,906.49	1,898.00
Total Maintenance Cost per Truck ($)	6,953.25	949.00
Total Maintenance Cost per Mile ($)	**0.283**	**0.069**

Breakdown of Maintenance Costs by Vehicle System		
Total Engine/Fuel-Related Systems (ATA VMRS 30, 31, 32, 33, 41, 42, 43, 44, 45, 65)		
Parts Cost ($)	1,272.00	77.48
Labor Hours	111.8	1.0
Average Labor Cost ($)	5,587.50	50.00
Total Cost for System ($)	6,859.50	127.48
Total Cost for System per Truck ($)	3,429.75	63.74
Total Cost for System per Mile ($)	**0.1397**	**0.0047**
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost ($)	0.00	0.00
Labor Hours	1.0	0.0
Average Labor Cost ($)	50.00	0.00
Total Cost for System ($)	50.00	0.00
Total Cost for System per Truck ($)	25.00	0.00
Total Cost for System per Mile ($)	**0.0010**	**0.0000**
Fuel System Repairs (ATA VMRS 44)		
Parts Cost ($)	54.66	6.65
Labor Hours	87.0	0.0
Average Labor Cost ($)	4,350.00	0.00
Total Cost for System ($)	4,404.66	6.65
Total Cost for System per Truck ($)	2,202.33	3.33
Total Cost for System per Mile ($)	**0.0897**	**0.0002**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost ($)	555.37	68.13
Labor Hours	6.5	1.0
Average Labor Cost ($)	325.00	50.00
Total Cost for System ($)	880.37	118.13
Total Cost for System per Truck ($)	440.19	59.07
Total Cost for System per Mile ($)	**0.0179**	**0.0043**

Breakdown of Maintenance Costs by Vehicle System (continued)	LNG 16119-20	New Diesel 16131-2
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts Cost ($)	247.26	0.00
Labor Hours	8.8	0.0
Average Labor Cost ($)	437.50	0.00
Total Cost for System ($)	684.76	0.00
Total Cost for System per Truck ($)	342.38	0.00
Total Cost for System per Mile ($)	**0.0139**	**0.0000**
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost ($)	322.55	0.00
Labor Hours	0.0	0.0
Average Labor Cost ($)	0.00	0.00
Total Cost for System ($)	322.55	0.00
Total Cost for System per Truck ($)	161.28	0.00
Total Cost for System per Mile ($)	**0.0066**	**0.0000**
Cooling System Repairs (ATA VMRS 42)		
Parts Cost ($)	32.84	2.70
Labor Hours	0.3	0.0
Average Labor Cost ($)	12.50	0.00
Total Cost for System ($)	45.34	2.70
Total Cost for System per Truck ($)	22.67	1.35
Total Cost for System per Mile ($)	**0.0009**	**0.0001**
Hydraulic System Repairs (ATA VMRS 65)		
Parts Cost ($)	59.32	0.00
Labor Hours	8.3	0.0
Average Labor Cost ($)	412.50	0.00
Total Cost for System ($)	471.82	0.00
Total Cost for System per Truck ($)	235.91	0.00
Total Cost for System per Mile ($)	**0.0096**	**0.0000**
Brake and General Air System Repairs (ATA VMRS 10, 13)		
Parts Cost ($)	93.78	0.00
Labor Hours	3.0	0.5
Average Labor Cost ($)	150.00	25.00
Total Cost for System ($)	243.78	25.00
Total Cost for System per Truck ($)	121.89	12.50
Total Cost for System per Mile ($)	**0.0050**	**0.0009**

Breakdown of Maintenance Costs by Vehicle System (continued)	LNG 16119-20	New Diesel 16131-2
Transmission and Clutch Repairs (ATA VMRS 23, 26)		
Parts Cost ($)	0.00	0.00
Labor Hours	0.3	0.0
Average Labor Cost ($)	12.50	0.00
Total Cost for System ($)	12.50	0.00
Total Cost for System per Truck ($)	6.25	0.00
Total Cost for System per Mile ($)	**0.0003**	**0.0000**
Inspections Only - no parts replacements (101)		
Parts Cost ($)	0.00	0.00
Labor Hours	66.3	16.3
Average Labor Cost ($)	3,312.50	812.50
Total Cost for System ($)	3,312.50	812.50
Total Cost for System per Truck ($)	1,656.25	406.25
Total Cost for System per Mile ($)	**0.0675**	**0.0297**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost ($)	65.71	30.57
Labor Hours	4.3	2.8
Average Labor Cost ($)	212.50	137.50
Total Cost for System ($)	278.21	168.07
Total Cost for System per Truck ($)	139.11	84.04
Total Cost for System per Mile ($)	**0.0057**	**0.0061**
HVAC System Repairs (ATA VMRS 01)		
Parts Cost ($)	41.50	0.00
Labor Hours	1.0	0.3
Average Labor Cost ($)	50.00	12.50
Total Cost for System ($)	91.50	12.50
Total Cost for System per Truck ($)	45.75	6.25
Total Cost for System per Mile ($)	**0.0019**	**0.0005**
Fifth Wheel Repairs (ATA VMRS 59)		
Parts Cost ($)	0.00	0.00
Labor Hours	0.3	0.0
Average Labor Cost ($)	12.50	0.00
Total Cost for System ($)	12.50	0.00
Total Cost for System per Truck ($)	6.25	0.00
Total Cost for System per Mile ($)	**0.0003**	**0.0000**

Breakdown of Maintenance Costs by Vehicle System (continued)	LNG 16119-20	New Diesel 16131-2
Lighting System Repairs (ATA VMRS 34)		
Parts Cost ($)	79.58	1.18
Labor Hours	5.0	0.3
Average Labor Cost ($)	250.00	12.50
Total Cost for System ($)	329.58	13.68
Total Cost for System per Truck ($)	164.79	6.84
Total Cost for System per Mile ($)	**0.0067**	**0.0005**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts Cost ($)	500.48	0.00
Labor Hours	2.0	0.0
Average Labor Cost ($)	100.00	0.00
Total Cost for System ($)	600.48	0.00
Total Cost for System per Truck ($)	300.24	0.00
Total Cost for System per Mile ($)	**0.0122**	**0.0000**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost ($)	2.02	0.00
Labor Hours	5.0	3.0
Average Labor Cost ($)	250.00	150.00
Total Cost for System ($)	252.02	150.00
Total Cost for System per Truck ($)	126.01	75.00
Total Cost for System per Mile ($)	**0.0051**	**0.0055**
Tire Repairs (ATA VMRS 17)		
Parts Cost ($)	801.42	451.27
Labor Hours	22.3	2.8
Average Labor Cost ($)	1,112.50	137.50
Total Cost for System ($)	1,913.92	588.77
Total Cost for System per Truck ($)	956.96	294.39
Total Cost for System per Mile ($)	**0.0390**	**0.0215**

Notes

1. The engine/fuel-related systems were chosen to include only those vehicle systems that could be impacted directly by the selection of fuel.

2. ATA VMRS coding is based on parts that were replaced. If no part was replaced in a given repair, then the code was chosen by the system being worked on.

3. In general, inspections (with no part replacements) were only included in the overall totals (not by system). 101 was created to track labor costs for PMA inspections.

4. ATA VMRS 02-Cab and Sheet Metal represents seats, doors, etc.; ATA VMRS 50-Accessories represents items such as fire extinguishers, test kits, etc.; ATA VMRS 71-Body represents mostly windows and windshields.

5. Average labor cost is assumed to be $50/h.

6. Costs covered by the prototype demonstration agreement are not included.

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