Raley's LNG Truck Fleet

Final Results

Produced for the U.S. Department of Energy (DOE) by the National Renewable Energy Laboratory (NREL), a U.S. DOE national laboratory

Alternative Fuel Truck Evaluation Project

Raley's LNG Truck Fleet: Final Results

Alternative Fuel Truck Evaluation Project

by

Kevin Chandler, Battelle
Paul Norton, National Renewable Energy Laboratory (NREL)
Nigel Clark, West Virginia University

March 2000

The authors wish to acknowledge the help and cooperation of the staff at the host site, and in particular Stan Sasaki and the Raley's office staff at the Distribution Center. The authors also acknowledge Ed Gamache at Ozark Trucking, and the editorial contributions of Vincent Brown at Battelle and René Howard at NREL.

World Wide Web: http://www.afdc.doe.gov
National Alternative Fuels Hotline: 1-800-423-1DOE

Notice

Available electronically at http://www.doe.gov/bridge

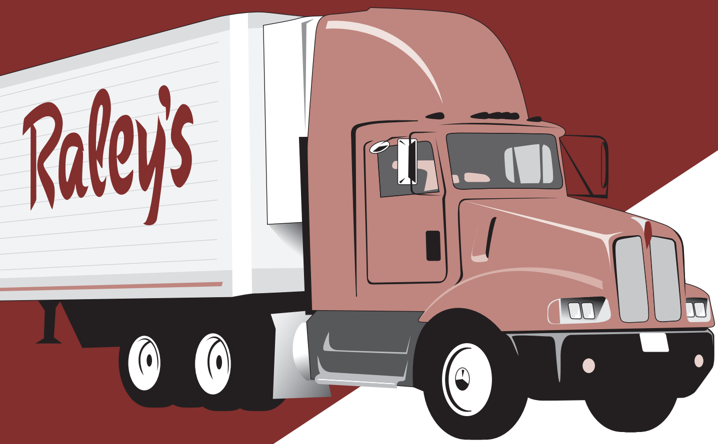
Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.ht

Table of Contents



Executive Summary

Raley's Supermarkets (Raley's), a large retail grocery company based in Northern California, began operating heavy-duty trucks powered by liquefied natural gas (LNG) in 1997, in cooperation with the Sacramento Metropolitan Air Quality Management District (SMAQMD). The U.S. Department of Energy (DOE) Office of Heavy Vehicle Technologies (OHVT) sponsored a research project to collect and analyze data on the performance, operation costs, and emissions, of eight of Raley's LNG trucks in the field. Their performance was compared with that of three diesel trucks operating in comparable commercial service.

Objective

The objective of the DOE research project, which was managed by the National Renewable Energy Laboratory (NREL), was to provide transportation professionals with quantitative, unbiased information on the cost, maintenance, operational, and emissions characteristics of LNG as one alternative to conventional diesel fuel for heavy-duty trucking applications.

In addition, this information should benefit decision makers by providing a real-world account of the obstacles encountered and overcome and the lessons learned in adapting alternative fuel trucks to a commercial site that had previously been geared toward diesel trucks. The field study at Raley's was part of DOE's ongoing Alternative Fuel Truck Evaluation Project.

Methods

Raley's leased its trucks from Ozark Trucking. Ozark's personnel performed maintenance on the trucks and cooperated in the data collection. In addition to the eight heavy-duty LNG trucks, Raley's used two LNG yard tractors at its Distribution Center. These yard tractors were very well-received by Raley's operators. Data were gathered from fuel and maintenance tracking systems daily for more than 1 year. Here are examples of the data parameters:

- Fuel consumption
- Mileage and dispatching records
- Engine oil additions and oil/filter changes
- Preventive maintenance action records
- Records of unscheduled maintenance (such as road calls) and warranty repairs.

The data collection was designed to cause as little disruption for the host site as possible. In general, staff members at Raley's and Ozark sent copies (electronic and/or paper) of data that had already been collected as part of normal business operations.

Results

Both the LNG and diesel fleets performed the work that Raley's expected of them during the evaluation period. The major difference in duty cycle operation was that, on average, the diesel trucks were driven more miles per day than the LNG trucks, but were used for fewer hours and visited fewer stores per day than the LNG trucks. The LNG trucks were used for shorter, more numerous trips at generally lower speeds. These differences affected the comparative energy efficiency of the fleets.

The LNG trucks were found to emit lower levels of oxides of nitrogen and particulate matter than the diesel trucks. By most other measures of operation, the diesel trucks performed better than the LNG trucks. The LNG trucks had lower energy equivalent fuel economy, greater fuel cost per mile driven, and greater maintenance costs per year and per mile driven compared with the diesel trucks.

Overall, the operating cost for the LNG trucks averaged $0.383 per mile, and the diesel trucks averaged $0.192 per mile, giving the diesel trucks an advantage of $0.191 per mile.

Lessons Learned

The LNG truck evaluation project gave Raley's, DOE, and other participants the opportunity to learn many lessons about using alternative fuels. Some highlights follow:

- Commitment at several levels within the organization is essential.
- Alternative fuel projects require creative, forward-thinking planning, not only to get started, but also to keep going.
- Learning about the fuel builds a good foundation for decision making.
- Comprehensive operating and safety training is essential. For example, training the drivers of LNG trucks in lower power engine operation was helpful.
- A team approach, including personnel within and external to the trucking company (such as manufacturer and vendor representatives), facilitates the start-up operation.
- A natural gas engine with a higher power rating would have improved the implementation and operation of the alternative fuel vehicles at this site.
- The LNG trucks provided lower than expected fuel economy, and thus lower than expected operating range between fuelings. Fueling station personnel and drivers indicated that they needed to know whether the truck had a full fuel load to maximize usage and avoid problems with running out of fuel.

Obstacles Overcome

One early problem with the LNG engines concerned their reliability in service. In response, Cummins, the engine supplier, changed several components and provided technical support. Engine problems were settled within a few months of start-up, and there were few failures for the remainder of the evaluation period.

Drivers remarked that the LNG trucks seemed under-powered compared to the diesel trucks. The LNG trucks had lower available torque and lower horsepower than the diesel control trucks, and this difference was noticeable to the drivers.

The LNG fuel cost more than diesel, and because Raley's was using a temporary LNG fueling station in the early part of the evaluation period, fueling was sometimes inconvenient. Raley's was constructing a permanent LNG fueling station with a larger capacity during the evaluation, but that station did not go into service until late in the year. The permanent station enabled Raley's to obtain LNG fuel at an average cost that was $0.10 per gallon less than the fuel from the temporary station.

Future LNG Operations at Raley's

At the end of the evaluation period, Raley's was looking at options to expand its LNG fleet. Raley's had held discussions with Cummins West, the engine supplier, regarding a joint research project to test one or two prototype 400-horsepower natural gas engines using the Westport high-pressure, direct-injection dual-fuel technology. This test is planned to begin late in 2000.

Overview

Raley's Supermarkets (Raley's), a large retail grocery company based in northern California, began operating trucks powered by liquefied natural gas (LNG) in 1997, in cooperation with the Sacramento Metropolitan Air Quality Management District (SMAQMD). For part of 1997 and all of 1998, the U.S. Department of Energy's (DOE) Office of Heavy Vehicle Technologies (OHVT) sponsored a research project to collect and analyze data on the performance, operating costs, and emissions of eight of Raley's LNG trucks in the field. Comparison data were also collected and analyzed on three similar diesel trucks at Raley's.

The study was the first of its kind, in that data were collected on LNG-fueled trucks that were hauling freight in heavy-duty commercial service over an extended time frame.

The purpose of this report is to provide transportation professionals with information on the cost, maintenance, operational, and emissions characteristics of LNG as one alternative to conventional diesel fuel for trucking applications. In addition, the report should benefit decision makers by providing a real-world account of the obstacles that were overcome and the lessons that were learned in adapting alternative fuel trucks to a site previously geared toward diesel trucks.

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:

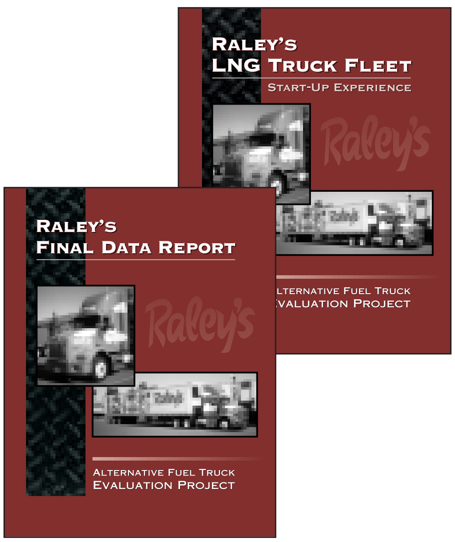
– Natural Gas Vehicle Coalition: http://www.ngvc.org/qa.html

– Alternative Fuels Data Center: http://www.afdc.doe.gov

– Zeus Development Corp./LNG Express: http://www.lngexpress.com/welcome.htm

– CH-IV Cryogenics: http://www.ch-iv.com/lng/lngfact.htm

This report is intended to summarize the results of the LNG study at Raley's. Further technical background, research methods, data, and detailed discussions are presented in a companion document (Battelle, July 1999).



Alternative Fuel Projects at DOE and NREL

On behalf of DOE, the National Renewable Energy Laboratory (NREL) managed the data collection, analysis, and reporting activities for the Raley's LNG truck evaluation. NREL is a DOE national laboratory.

Several types of alternative fuels have been evaluated by NREL and participating companies across the United States. These fuels include LNG, CNG, biodiesel, ethanol, and propane (liquefied petroleum gas, or LPG).

One of NREL's missions is to assess the performance and economics of alternative fuel vehicles objectively so that

- Fleet managers can make informed decisions when purchasing alternative fuel vehicles.
- Alternative fuel vehicles can be used more widely and successfully in the future to reduce U.S. consumption of imported petroleum and to benefit users and the environment.

The Truck Evaluation Project

The overall objective of the ongoing DOE/NREL Alternative Fuel Truck Evaluation Project is to compare heavy-duty trucks using an alternative fuel with those using conventional diesel fuel.

So far, the five host sites listed in Table 1 have been selected to participate.

These sites have been selected according to the kind of alternative fuel technology in use, the types of trucks and engines, the availability of diesel comparison ("control") vehicles, and the trucking company's interest in using alternative fuels.

After analysis, peer review, and DOE approval, results from each site will be published separately.

Host Site Profile: Raley's Supermarkets

The participating host site for this study was Raley's, a growing, privately owned grocery retailer with headquarters in West Sacramento, California. Raley's is the 38th largest supermarket chain in the United States and the 10th largest private employer in California.

Table 1. Host Sites in the DOE/NREL Truck Evaluation Project

Host Organization	City, State	Fuel	Chassis	Engine
Raley's Supermarkets	Sacramento, CA	LNG	Kenworth	Cummins L 10-300G
Pima Gro Systems, Inc./Orange County Sanitation District	Fountain Valley, CA	CNG/Diesel	White/GMC	Caterpillar 3176 Dual-Fuel
Waste Management	Washington, PA	LNG	Mack	Mack E7G-325
United Parcel Service	Hartford, CT	CNG	Freightliner	Cummins B5.9G
Ralphs Grocery Company	Riverside, CA	Low-sulfur diesel/catalyzed particulate filters	Sterling	Detroit Diesel Series 60

At the time of the study, Raley's operated more than 100 stores and employed about 14,000 people. At that time, Raley's was operating in the Sacramento, San Jose, and Lake Tahoe, California, areas as well as in Reno, Nevada. In 1999, Raley's was in the process of adding operations in Las Vegas, Nevada, and in Albuquerque and Las Cruces, New Mexico.

The trucking operation at Raley's expanded during the evaluation by adding service to Nob Hill grocery locations in mid-1998. Stores currently operated by the company include Raley's Superstores and Supermarkets, Bel Air Markets, Food Source, and Nob Hill Foods. By the end of this evaluation, Raley's had a 64-truck fleet, of which 56 were diesel and 8 were LNG.

Raley's LNG Trucks

In April 1997, Raley's began operating California's first fleet of commercial trucks fueled by LNG. Specifically, Raley's operated eight heavy-duty LNG trucks. Also evaluated as a "control group" in this study were three of Raley's heavy-duty diesel trucks.

Raley's operated all the trucks taking part in the study under a lease arrangement with the trucks' owner, Ozark Trucking. In addition to the eight heavy-duty LNG trucks being studied, Raley's leased two LNG yard tractors (Ottawa trucks with Cummins B5.9G engines), which were not formally evaluated in this study.

Table 2 shows the general specifications of the eight heavy-duty LNG trucks and the three diesel control trucks evaluated at Raley's. As shown in Table 2, the LNG trucks in the study were Kenworth T800s, whereas the diesel control trucks were T400s. A Kenworth engineer described the differences between the T400 and T800 models as minor.

The study compares LNG trucks with L10 engines to diesel trucks with M11 engines. The L10 diesel truck engine was discontinued prior to the start of the study. We contacted Cummins Engine

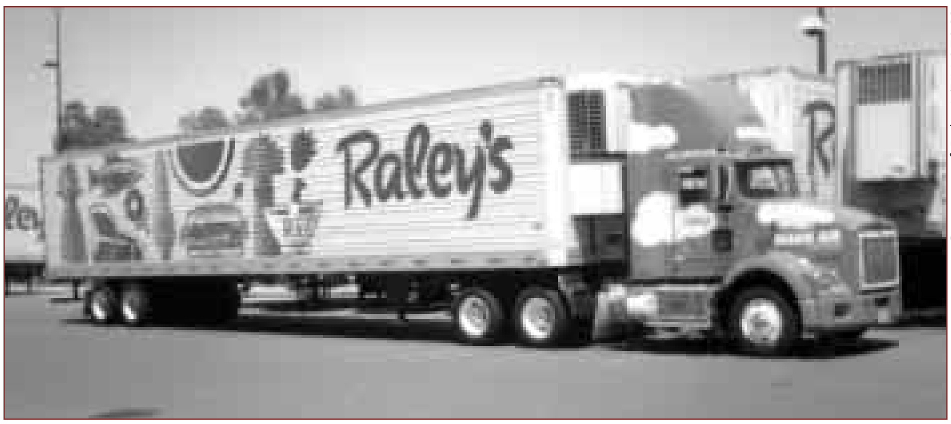
Table 2. Vehicle System Descriptions—Raley's

Description	LNG Trucks	Diesel Control Trucks
Number of Trucks in Study	8	3
Chassis Manufacturer/Model	Kenworth T800, Class 8	Kenworth T400, Class 8
Chassis Model Year	1997	1996
Engine Manufacturer/Model	Cummins L10-300G	Cummins M11-330
Engine Ratings Max. Horsepower Max. Torque	 300 hp @ 2100 rpm 900 lb-ft @ 1300 rpm	 330 hp @ 1600 rpm 1250 lb-ft @ 1200 rpm
Fuel System Storage Capacity	174 LNG gallons total (104 diesel energy equivalent gallons); 2 LNG saddle tanks form MVE, Inc.	114 gallons
Transmission Manufacturer/Model	Fuller RT11710B, 10 speed	Fuller RTL12610B 10 speed
Catalytic Converter Used?	No	No
Vehicle Purchase Price in Comparison to Diesel	+$35,000	–

Company for suggestions on comparable engines. Cummins's chief engineer of heavy-duty natural gas engines identified the M11 as the best comparison engine because it represented the current diesel technology. The M11 engine is very similar to the L10 engine but has a longer piston stroke for increased displacement.

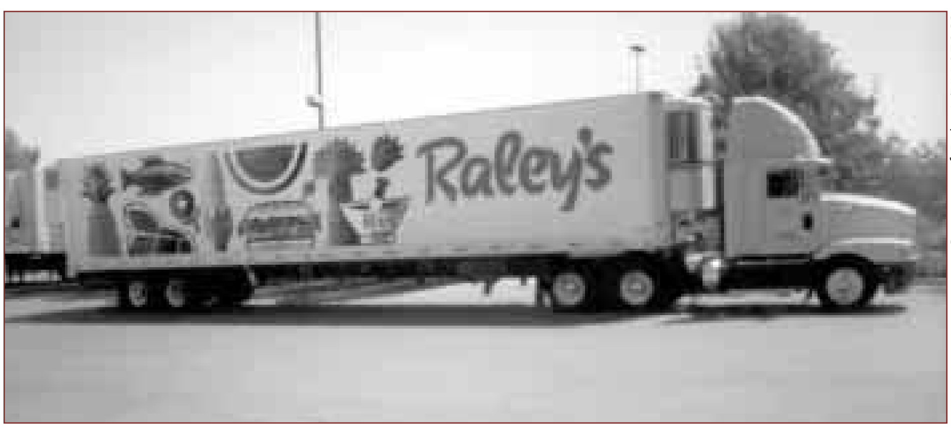
The diesel vehicles started operation in late 1995 and early 1996. The diesel trucks at Raley's were nearly a year older than the LNG trucks at the time of the study. Historical maintenance data were collected for the diesel trucks, so that the maintenance cost comparisons would match trucks of similar age, and costs were calculated using constant dollars for labor and materials.

LNG



Courtesy of Raley's/PIX 05963

Diesel



Courtesy of Raley's/PIX 05962

During the evaluation, Raley's LNG trucks were used for routes in the Sacramento area and nearby suburbs. SMAQMD requested this routing plan to maximize the emissions benefits within the Sacramento Air Basin, which is part of a federal ozone nonattainment area. The diesel control trucks were used to service grocery locations south and west of Sacramento on routes over terrain similar to that of the routes covered by the LNG trucks, but to destinations that were generally farther from the distribution center. This difference in territory significantly affected the comparative economics of operating the two sets of trucks being evaluated, as discussed in more detail later in this report.

Raley's Involvement in Air Quality Improvement

Because Raley's has a corporate history and tradition of environmentally conscious practices, such as recycling and energy-awareness programs, the company was a fitting site for an alternative fuels evaluation project. Raley's has received awards for its environmental stewardship from organizations such as the American Lung Association of Sacramento-Emigrant Trails.

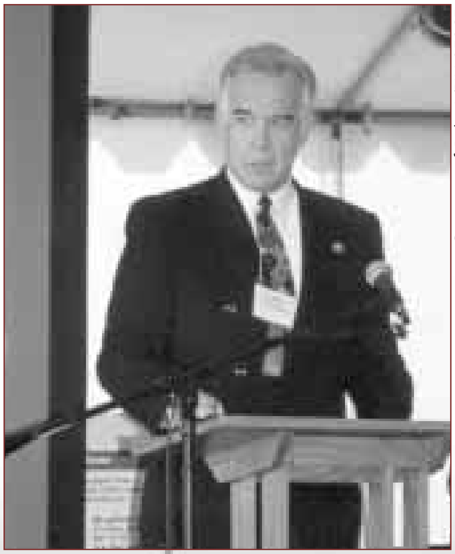
Some months before the LNG evaluation began, Raley's manager of environmental and regulatory affairs discussed the idea of alternative fuels with a representative of the Mobile Source Division at SMAQMD. Together, Raley's and SMAQMD framed the project and developed an action plan.

The NREL data collection and analysis project benefited from Raley's corporate commitment to alternative fuels. According to one Raley's representative, Raley's is interested in helping to demonstrate the effectiveness of LNG fuel, and in being seen as a leader in using emissions control technology.

Raley's grocery distribution operations (of which the LNG trucks are a part) are typical of pick-up and delivery operations. The trucking at Raley's is considered "less-than-truckload." This means that trucks are typically loaded to a weight less than the maximum allowed on the highway. Pick-up and delivery trucking operations make up 40% to 50% of U.S. trucking.

SMAQMD supported the Raley's LNG project through a grant of $600K, which was put toward the incremental cost of the LNG trucks (eight heavy-duty tractors and two yard tractors) and the construction of a permanent LNG refueling station. The LNG equipment added $35K to the cost of a tractor—the diesel trucks each cost $72K and the LNG trucks cost $107K each—and the additional cost of each yard tractor was $25K, for a total of $330K. The other $270K was applied to the cost of constructing the permanent LNG refueling station at Raley's. The SMAQMD grant was required to get the program started, but it did not cover all of the start-up costs for the LNG operation.

California Legislator Larry Bowles was one of the speakers at Raley's celebration to kick off the LNG program.



Courtesy of Raley's/PIX 05965

Courtesy of Raley's/PIX 05964

Project Design and Data Collection

Data were gathered from Raley's and Ozark Trucking's fuel and maintenance tracking systems daily. Here are some examples of the data parameters:

- Diesel fuel consumption by vehicle and fill
- LNG fuel consumption by vehicle and fill
- Mileage data from every vehicle
- Dispatching logs
- Engine oil additions and oil/filter changes
- Preventive maintenance action (PMA) work orders, parts lists, labor records, and related documents
- Records of unscheduled maintenance (e.g., road calls)
- Records of repairs covered by manufacturer warranty.

The data collection was designed to cause as little disruption for Raley's as possible. Data were sent from the trucking site to Battelle for analysis. In general, staff at Raley's and Ozark sent copies (electronic and/or paper) of data that had already been collected as part of normal business operations.

Raley's staff had access to all data being collected from their site and other data available from the project. Summaries of the data collected, evaluations, and analyses of the data were distributed to designated staff at Raley's for review and input.

The study design included the tracking of safety incidents affecting the vehicles or occurring at Raley's fueling station or in the maintenance facilities. However, no safety incidents were reported during the data collection period.

Raley's Facilities and Bulk Fuel Storage

The trucks evaluated in this study were based at Raley's Distribution Center, where LNG storage and fueling facilities are located. Maintenance and repair activities for both LNG and diesel trucks were performed at Ozark Trucking's facility.

Raley's Distribution Center has approximately 400,000 square feet of under-roof floor space. The trucking fleet includes 64 tractors and 104 refrigerated trailers. Approximately 90 trips begin at the Distribution Center daily. The center's staff, including drivers, warehouse personnel, and administrative staff, number approximately 340.

The trucks being evaluated spent approximately 12 hours per day at the Distribution Center, and 12 hours per day away from the Distribution Center.

The trucks being evaluated spent approximately 3 to 3.5 hours per month at the Maintenance Center at Ozark Trucking.

During most of the LNG evaluation period, refueling for the LNG trucks was provided by a 5,000-gallon Quick Response System (QRS) temporary station (manufactured by MVE, Inc., and provided by Cummins West). This temporary refueling station was located at Raley's Distribution Center.

A permanent, 13,000-gallon LNG refueling station was under construction at the Distribution Center through most of the data collection period. Construction of the permanent station was completed in November 1998, near the end of the data collection period, at an estimated cost of $350,000.

Distribution Center (Raley's)

Courtesy of Raley's/PIX 05961

Maintenance Center (Ozark Trucking)

Courtesy of Raley's/PIX 05960

With the completion of the permanent refueling station, Raley's was able to receive a full tanker truckload of LNG fuel (10,000 gallons) instead of a partial load (5,000 gallons). The full loads of LNG fuel cost $0.10 per gallon less (reduced from $0.575 to $0.475 per LNG gallon) than the partial loads, significantly reducing fuel costs. Fueling station effects are discussed in the section on fuel economy.

Raley's planned for the construction of its permanent LNG fuel station to be completed in the spring of 1997 in time for the start of operation of the LNG trucks in April 1997. However, several issues with the design contractor delayed the beginning of construction until the fall of 1997. Once construction had begun, several issues arose including building codes, parts availability, and a few changes to the original design of the station.

The permanent LNG fuel station was essentially complete in May 1998, but required several minor modifications to optimize operating efficiency. Most of the problems with this station revolved around the design contractor. However, a few delays came from parts ordering and working with the local code officials to get the operation of the station approved. A separate contractor was hired to optimize operation of the station. Raley's has reported that the station is operating well and meeting the fleet's needs.

QRS

Courtesy of Raley's/PIX 05959

Permanent Station

Courtesy of Raley's/PIX 05958

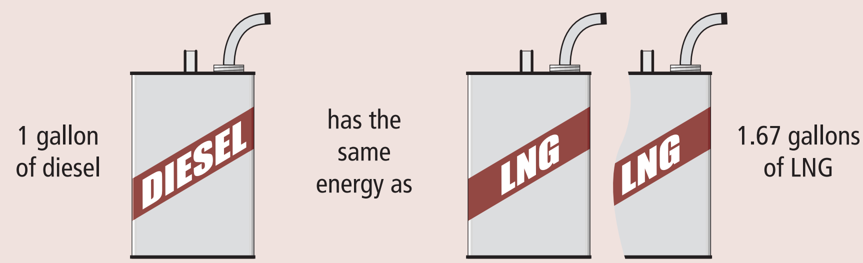
Project Start-up at Raley's

The LNG trucks began operating in April 1997. Early in the deployment of the LNG trucks, several part quality and hardiness issues arose. Under the original equipment warranty, Cummins (the manufacturer of the LNG engines) changed wastegate valves, sensors, spark plugs and wires, and ignition modules on all of the trucks.

These start-up issues were resolved by January 1998. Trends observed in driver complaints confirmed that engine operation improved after that date. Because of the difficulties in project start-up, the data analysis for both diesel and LNG trucks focuses on the 12-month period from January to December 1998, which was considered to be the "data clean point" for the evaluation.

What Is a Diesel Equivalent Gallon?

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



LNG Engine Issues

The primary difference between the LNG and diesel trucks noted by drivers during the project start-up was the significantly lower power of the LNG trucks. Because the engines of the LNG trucks had lower horsepower and torque ratings than the engines of the diesel trucks, this result is not surprising. However, the LNG trucks did have sufficient power to complete their assigned routes. Tracking indicated that driver complaints of low power from the LNG trucks were much more frequent when changes in drivers and routes caused operators who had been driving diesel trucks to begin driving the LNG trucks.

During the start-up of operations at Raley's, the LNG trucks had problems that resulted in the engines running rough. In addition, the engines' low power sometimes prevented them from going faster than 20 mph. Troubleshooting revealed several issues. The wastegate valve design was hardened and the ignition control module used on the LNG trucks was found to have an electrical quality control problem. While these problems were being investigated, several sets of spark plugs and wires, as well as oxygen sensors, were replaced to try to alleviate the low power problem. Once the wastegate and ignition control module problems were resolved, the engines were much more reliable.

Range and Fuel Gauge Issues

The LNG trucks provided lower than expected fuel economy, and thus lower than expected operating range between fuelings. Some out-of-fuel incidents occurred among the LNG trucks being evaluated. This resulted in road maintenance calls and labor/towing expenses.

With a fleet average fuel economy of 4.32 miles per diesel equivalent gallon for the LNG engines, and a fuel tank capacity of 104 diesel equivalent gallons of LNG, the LNG trucks had an operating range of about 450 miles. For Raley's diesels (7.02 miles per gallon, with 114 gallon tank capacity), this range was about 800 miles. The LNG trucks averaged 195 miles per working day. The diesel trucks averaged 256 miles per day. Thus the LNG trucks could operate for about 2.3 days per fuel fill at most, compared with 3.1 days per fuel fill for the diesel trucks. Unreliable fuel gauges on some LNG trucks complicated the range problem. Fueling station personnel and drivers indicated that they needed to know whether the truck had a full fuel load to maximize usage and reduce problems with running out of fuel.

At times, the fuelers at Raley's had difficulty determining whether there was a full load of LNG on board the LNG trucks. Each LNG truck has two LNG tanks, one on either side of the truck. In many cases, the fueler would simply put fuel into the truck until the fueling system automatically shut down. This procedure should fill both tanks. However, the incoming fuel enters the tank that offers less resistance, because of small differences in pressure between the two tanks. If the pressure in the empty (higher pressure) tank exceeds that of the bulk storage tank, fuel cannot be transferred into it. This pressure difference eventually results in one tank staying empty while the other is full.

Without a reliable fuel gauge, knowing that one of the tanks did not take fuel was very difficult. The LNG truck would be assumed to have a full load of fuel and in actuality, would only have a half load of fuel at best. Raley's worked through this problem by using the vent stack on the trucks to release the higher pressure gas in the tanks before and during fueling of the LNG trucks. This was only a problem with the temporary (QRS) fueling system. The permanent refueling station had enough pumping pressure to overcome the gas pressures in the LNG fuel tanks on the trucks.

LNG Losses to the Atmosphere

Raley's found measurement of LNG fuel to be an issue. The temporary fueling station (QRS) required a significant amount of natural gas to be vented to the atmosphere when receiving fuel in bulk from the tanker truck. The fuel lost from the refueling station was not measured.

This venting did not affect the measurement of LNG consumed by Raley's trucks. However, Raley's paid for all the LNG unloaded from the tanker truck. This loss from the QRS was probably on the order of $0.01 per gallon of LNG or less.

A small amount of LNG fuel was also lost to the atmosphere when refueling the trucks from the

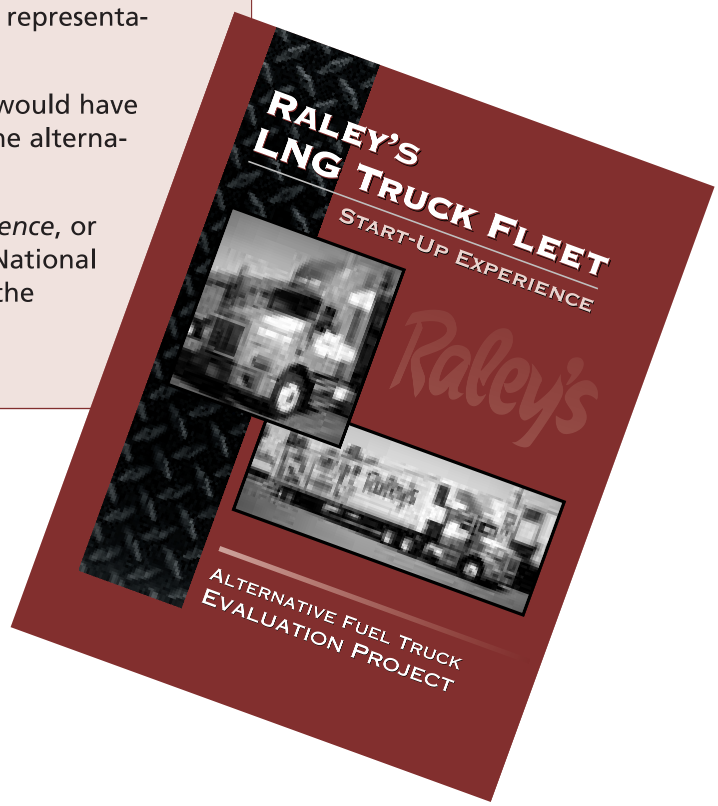
Lessons Learned at Start-Up

- Commitment at several levels within the organization is essential.
- Alternative fuel projects require creative, forward-thinking planning not only to get started, but also to be sustained. Some problems during the initial program development may seem insurmountable, because there is no precedent.
- Learning about the fuel builds a good foundation for decision making.
- Comprehensive operating and safety training is essential.
- Alternative fuel projects offer tremendous opportunity to educate the public about benefits of the fuel and the sponsoring company.
- It is important to know the regulations of the local area.
- A team approach, including personnel within and external to the trucking company (e.g., manufacturer and vendor representatives), facilitates the start-up operation.
- A natural gas engine with a higher power rating would have improved the implementation and operation of the alternative fuel vehicles at this site.

For a copy of *Raley's LNG Truck Fleet Start-Up Experience*, or of *Raley's LNG Truck Site Final Data Report*, call the National Alternative Fuels Hotline at 1-800-423-1DOE or visit the Alternative Fuels Data Center Web site at http://www.afdc.doe.gov

QRS. Having the tank vents open during refueling (vent filling) released natural gas from the fuel tank to the atmosphere.

This loss of gas through the truck tank vent reduced the fuel economy of the LNG trucks slightly; the amount of the LNG fuel vented to atmosphere during fueling was probably less than 1% of the fuel loaded on-board the truck. Vent filling was no longer required after the permanent fueling station was put in service.



Evaluation Results

Both the LNG and the diesel fleets did the work that Raley's expected of them during the evaluation period. The major difference in operations was that, on average, the diesel trucks were driven more miles per day than the LNG trucks, but were used for fewer hours and visited fewer stores per day than the LNG trucks. The LNG trucks were used for shorter, more numerous trips at generally lower speeds. This difference affected the comparative energy efficiency of the fleets.

The LNG trucks were found to emit less NO_x (oxides of nitrogen) and particulate matter (PM) than the diesel trucks. By most other measures of operation, the diesel trucks performed better than the LNG trucks. The LNG trucks had lower energy equivalent fuel economy, greater fuel cost per mile driven, and greater maintenance costs per year and per mile driven compared with the diesel trucks.

Overall, the operating cost for the LNG trucks averaged $0.383 per mile, and the diesel trucks averaged $0.192 per mile, giving the diesel trucks an advantage of $0.191 per mile.

Actual Truck Use in Commercial Service

Each truck at Raley's was commonly used up to 6 days per week and 2 shifts per day. The trucks departed the Distribution Center loaded and returned nearly empty (returning with empty pallets and spoiled or damaged goods) unless the truck was used to back haul goods to the Distribution Center.

Because the LNG trucks operated only in the Sacramento area and the diesel control trucks used in this study traveled on similar terrain, but went farther outside the Sacramento area to make deliveries and pick-ups, the LNG trucks accumulated significantly lower numbers of miles per calendar month. The LNG trucks also operated at lower average speeds than the diesel control trucks.

Truck usage data were analyzed per trip, per day, and per month, as shown in Figures 1 and 2. The data shown are for days that the trucks were used and thus do not account for any downtime (e.g., weekends, holidays, or maintenance/repair days). A trip is defined as the route for each truck leaving the Distribution Center, making deliveries (or picking up), and returning to the Distribution Center.

The data in Figure 1 indicate that each LNG truck made an average of three trips in a day. The LNG trucks operated nearly 12 hours per day, deliveries were made to (or from) 6 to 7 stores, mileage per day averaged 195 miles per truck, and a back haul was made on every third truck on any given day of operation.

During the same period, the diesel trucks were used mostly on one fairly long trip and another very short route in a given day. Thus for the diesel trucks there is little difference between per-trip and per-day mileage. The diesel trucks averaged 10 hours, 4 to 5 stores, 256 miles per truck, and one back haul daily per truck.

Back-haul values are significant because they represent loaded miles, as opposed to empty miles. The greater the number of back hauls, the greater the load on the truck at a given time.

Average Speed

Raley's trucks were equipped with an onboard computer monitoring system from Cadec Corporation (Londonderry, NH). This monitoring system tracked vehicle operation, idle time, and the stores that were serviced by the truck. At the start of operation of the LNG trucks (May to July 1997), the average speeds during vehicle operation (excluding time at the loading docks) were 45 mph for the diesel control trucks and 39 mph for the LNG trucks. Toward the end of the study (November 1998) the diesel control trucks showed an average speed of 40 mph, and the LNG trucks had an average speed of 37 mph. This difference in speed between the diesel and LNG trucks is most likely a result of LNG trucks servicing more stores per day, as indicated in the trip data.

Monthly Miles Driven

The LNG trucks were driven consistently about 27% fewer average monthly miles per truck (see Figure 2). Between March and August 1998, the LNG trucks consistently averaged 5,000 miles,

Figure 1. Vehicle usage

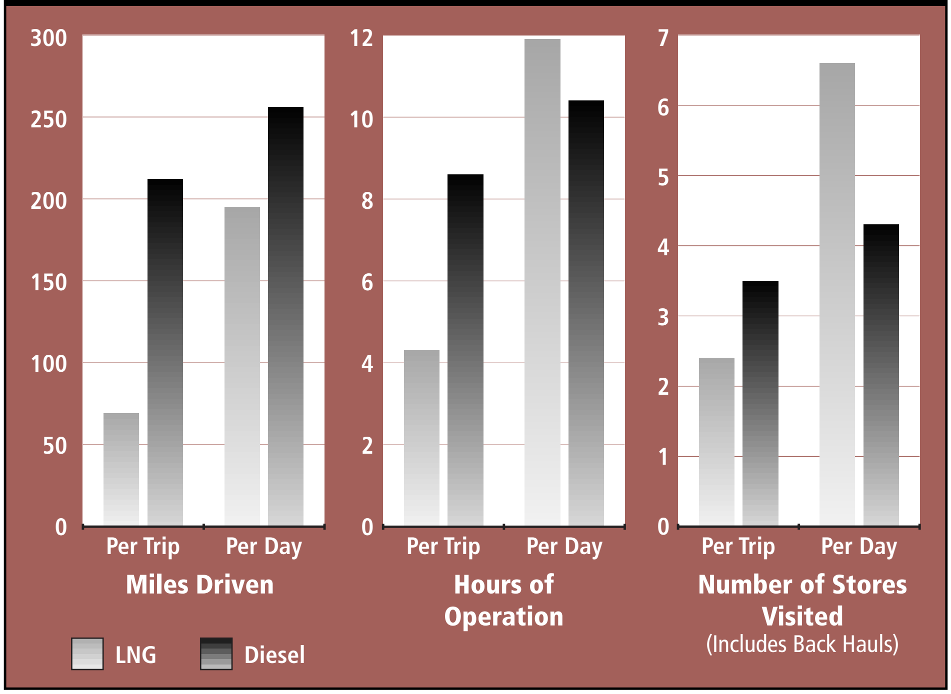
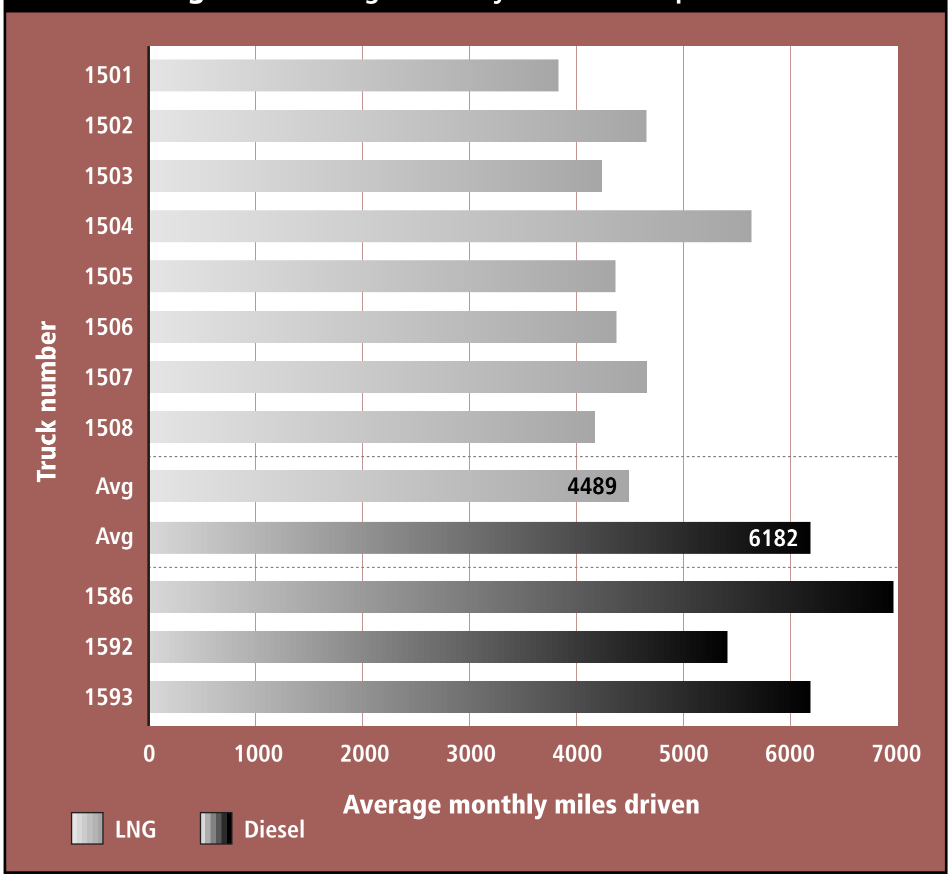


Figure 2. Average monthly miles driven per truck



and the diesel trucks increased their average monthly mileage significantly to nearly 8,000 miles.

This change in the diesel truck usage as well as the slight increase in the LNG truck usage were directly related to the addition of the Nob Hill stores into Raley's operation. The average monthly miles driven for the diesel trucks returned to about 5,000 miles per truck by the end of the data collection period, in part because more diesel trucks were added to the fleet to better accommodate the Nob Hill stores.

Fuel Economy, Maintenance, and Costs

The LNG trucks used more fuel per mile, and the fuel they used cost more per mile than the diesel fuel used in the diesel trucks. The better fuel economy for diesel trucks was confirmed both in the field and on a dynamometer used for emissions testing.

Fuel costs were affected by unusually low diesel fuel prices during the study period, and by the increased cost for LNG delivered in relatively small quantities to the temporary fueling station. LNG fuel prices dropped by $0.10 per gallon as Raley's larger capacity, permanent fueling station went into service.

Engine oil consumption for the LNG engines was in line with the company's experience in diesel engines.

Fuel Economy

The LNG trucks consumed 38% more fuel per mile on an energy equivalent basis than did the diesel trucks. Figure 3 summarizes the fuel economy for both fleets, in miles per gallon.

Fuel economy measurements made at Raley's as part of the emissions testing on a chassis dynamometer (described in detail in Appendix H of the Final Data Report, July 1999) coincide closely with the difference in fuel economy seen in field operations. Specifically, a two-part emissions test showed the LNG trucks averaging about 33% lower energy equivalent fuel economy than the diesel trucks over the West Virginia University (WVU) 5-mile driving route. In transit buses with the L10 natural gas engines, the energy equivalent fuel economy has been 20% to 25% lower for natural gas vehicles compared to similar diesel vehicles (NREL 1996; Motta et al. 1996).

Several factors may be contributing to the lower fuel economy of the LNG trucks.

1. The LNG truck engines are throttled and spark ignited with a relatively low compression ratio (about 10.5 to 1). This strategy is needed because of the low cetane number and the high octane number of natural gas. The diesel engines are inherently more efficient because they have no throttle and are compression ignited with a relatively high compression ratio (about 16.1 to 1).
2. Drivers may work the LNG engines harder to "keep up" with the performance expected from the higher powered diesel trucks they are accustomed to driving.
3. As discussed previously, the LNG trucks were used

somewhat differently than the diesel trucks.

4. Losses from vent filling of the LNG trucks may also have affected the in-use fuel economy results.

The results of the chassis dynamometer tests imply that factors 3 and 4 are not large because a similar fuel economy decrease was observed when using identical duty cycles for the LNG diesel trucks and using a carbon balance method rather than fueling records to calculate fuel use.

Each of Raley's LNG trucks used an average of 77 gallons of LNG (46 diesel equivalent gallons) per day of operation, based on 6 days of operation per week.

Fuel Cost per Gallon

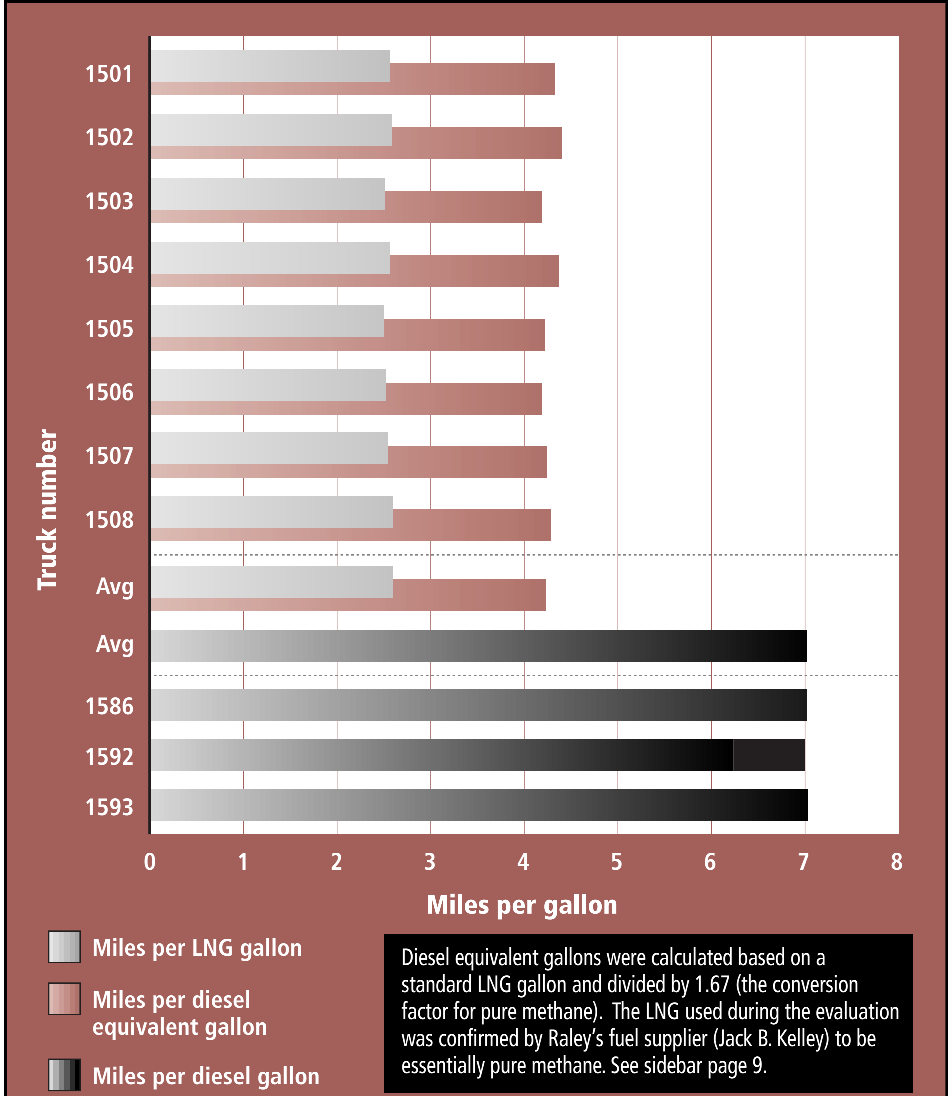
Including taxes, LNG costs averaged $0.74 per gallon ($1.24 per diesel equivalent gallon) and diesel costs averaged $1.01 per gallon during the 12 months of the study. However, these fuel costs may not be representative of typical LNG and diesel operations.

Fuel Cost per Mile

The fuel cost was $0.287 per mile for the LNG trucks, essentially double that of the diesel trucks at $0.144 per mile. Fuel cost per mile is derived from the volume of fuel used, the cost of that fuel per gallon, and the number of miles that the trucks have traveled using the fuel.

During the evaluation period, the average cost for LNG was much higher than the average cost for diesel. Using potential future fuel prices of $0.35 per LNG gallon plus $0.179 per LNG gallon tax ($0.88 per diesel equivalent gallon with tax) and $1.50 per gallon of diesel (including tax), Raley's fuel cost per mile would be 5% lower for the LNG trucks.

Figure 3. Fuel economy



Diesel equivalent gallons were calculated based on a standard LNG gallon and divided by 1.67 (the conversion factor for pure methane). The LNG used during the evaluation was confirmed by Raley's fuel supplier (Jack B. Kelley) to be essentially pure methane. See sidebar page 9.

Engine Oil Consumption and Cost

On average, the LNG trucks consumed 1.02 quarts of engine oil per 1,000 miles of operation. Representatives from Cummins, Raley's, and Ozark Trucking indicated that engine oil consumption around 1 quart per 1,000 miles is as good as or better than can be expected for heavy-duty trucking. Engine oil consumption for the diesel trucks was not tracked on an individual basis.

Oil for the LNG engines costs more than twice as much as oil for the diesel engines: $1.67 per quart for the LNG engines and $0.81 per quart for the diesel engines. The higher cost for the LNG engine oil results from the relatively small market share of heavy-duty natural gas engines, along with a special, low-ash oil requirement. However, LNG engine oil consumption costs were very low compared to the fuel and maintenance costs.

LNG Fuel Cost Factors

During the early part of the evaluation, Raley's purchased LNG in quantities less than a full truckload because of the limited capacity of the QRS temporary fueling station (5,000 gallons). Transportation costs for a partial truckload of LNG were the same as those for a full truckload (10,000 gallons), so the transportation cost per gallon of LNG delivered to the QRS was much higher than the cost per gallon at the permanent fueling station, which has a 13,000-gallon capacity. Use of the permanent station lowered Raley's LNG cost to $0.65 per gallon with tax ($1.09 per diesel equivalent gallon).

The LNG fuel cost could have been reduced even further had fuel been available from a source closer to Raley's.

Technologies now being developed may further lower the cost of LNG. For example, small-scale liquefaction may eliminate the need to transport LNG over great distances. LNG produced by small-scale liquefaction has been estimated to cost as little as $0.35 per LNG gallon delivered ($0.58 per diesel equivalent gallon).

Changes in Diesel Prices

During the data collection period, diesel costs started high, as high as $1.29 per gallon including tax, and dropped to very low levels, as low as $0.89 per gallon including tax (see Figure 4). The cost of diesel fuel was quite low during most of the data collection period. As a point of reference, however, on March 31, 1999, the diesel price at Raley's was $1.38 per gallon with taxes. Also, diesel fuel prices in California have historically been volatile and have recently climbed over $1.50 per gallon. This shows that diesel prices are subject to variability, which affects the cost of diesel and the operations comparison.

Maintenance Costs

Maintenance costs were generally higher for the LNG trucks than for the diesel control trucks. Maintenance data were collected and analyzed for a 12-month period near when the LNG trucks entered service. Because the diesel trucks were nearly a year older than the LNG trucks, historical maintenance data were collected for the diesel trucks. Because of the time difference, labor and parts costs for maintenance were normalized using constant rates and dollar values.

Raley's and Ozark trucking arranged for quarterly preventive maintenance actions (PMAs) to be performed on every truck. The PMAs, then, were conducted on a calendar basis, not on a mileage basis. For the DOE/NREL evaluation, PMAs 4 through 7 were analyzed, representing 1 year of operation after the clean point.

As detailed in Table 3, odometer readings for the LNG trucks were approximately 35,000 miles at the beginning of the maintenance analysis and approximately 89,000 miles at the end of the year. For the diesel trucks, the beginning readings were approximately 55,000 miles and the ending readings were approximately 129,000 miles.

Maintenance data have been analyzed by truck, by mile driven, and by the truck system involved. Warranty repairs paid for by the LNG truck and engine manufacturers were also tracked, as were driver complaints regarding both the LNG and diesel trucks. Warranty repair costs were not included in the cost analysis.

Maintenance Cost by Vehicle System

Figure 5 shows details of the maintenance costs for the LNG and diesel trucks, organized by various systems. Engine/fuel systems showed the greatest disparity in maintenance costs between LNG and diesel trucks; all other systems were fairly comparable, as discussed below.

The maintenance cost analysis was used to investigate higher costs for maintenance by vehicle system. These higher costs indicate potential reliability problems for some systems.

Parts and labor hours per truck were consistently much higher for the LNG trucks (4.1 times higher). Because of the

Figure 4. Average monthly diesel cost per gallon

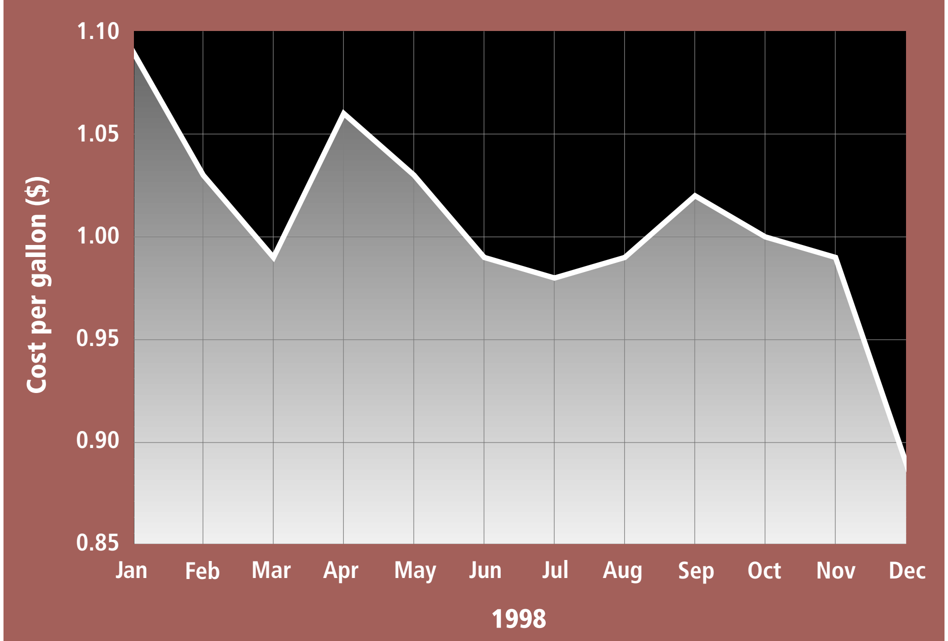


Table 3. Truck Life Used in Analysis

	Truck No.	Start Date	Odometer	End Date	Odometer
LNG	1501	12/97	31,996	12/98	78,028
	1502	12/97	32,221	1/99	88,496
	1503	12/97	34,538	12/98	88,203
	1504	12/97	40,877	12/98	106,730
	1505	1/98	25,842	1/99	78,505
	1506	12/97	35,468	1/99	89,674
	1507	12/97	36,407	12/98	94,926
	1508	12/97	41,956	12/98	92,934
Diesel	1586	3/96	58,074	3/97	131,054
	1592	6/96	49,419	5/97	116,971
	1593	5/96	59,159	4/97	141,471

high maintenance costs for the engine/fuel-related systems for the LNG trucks, these costs made up nearly 40% of the total maintenance costs. In contrast, the diesel maintenance costs for engine/fuel-related systems represented 14% of the overall maintenance costs for those trucks.

The engine/fuel-related systems maintenance costs are the most important comparison for understanding extra costs associated with implementing LNG trucks into the fleet. These are the systems expected to be affected by the new fuel system, engine, and electrical system for LNG operation.

The high engine/fuel-related systems maintenance costs for the LNG trucks were caused mostly by the non-lighting electrical system costs. The non-lighting electrical systems include charging, cranking, and ignition systems. The electrical costs included 15 sets of six spark plug replacements for normal PMA (recommended every 18,000 miles of operation) at a cost of $164 per set. There also were four sets of wires for the spark plugs replaced for normal PMA (recommended every 72,000 miles of operation) at a cost of $709 per set.

During the data collection, 23 batteries were replaced on the LNG trucks at a cost of $67.95 each. The battery replacements were most likely caused by the use of the methane detection system on-board the vehicle, which operates even when the truck is not in use. Accelerated consumption of batteries should be expected based on the operation of the methane detection system. In contrast, the diesel trucks had one non-lighting electrical maintenance action total during the data collection period: one of the trucks had a starter relay replaced.

The fuel and engine systems maintenance costs were significantly higher for the LNG trucks (3 times higher for fuel and 1.9 times higher for engine on a per truck basis). These higher costs were caused by labor for troubleshooting of fuel leaks (small leak repair and investigation for the methane detection system activating), running out of fuel, and complaints about engine low power and rough running. The diesel truck maintenance costs for the fuel and engine systems consisted almost entirely of fuel filters, oil filters, and engine oil costs for preventive maintenance. There were very few costs for unscheduled maintenance problems. Unscheduled maintenance costs for the diesel engine system were based on 0.6 hours, and the fuel system had 1.3 hours and $366.73 to replace a throttle pedal and assembly.

PMA Inspections—This category consists only of labor for PMA inspections of the vehicles. Because each truck received the same number of PMAs during the analysis period, the per-truck costs were essentially the same.

Cab, Body, and Accessories Systems; Lighting System—The LNG and diesel trucks costs for these systems were about the same per truck.

Frame, Steering, and Suspension Systems—The diesel trucks were essentially the same in per-truck costs. Each fleet had one leveling valve replaced, accompanied by a few labor hours.

Axle, Wheel, and Driveshaft Systems—The diesel trucks had higher per-truck costs for these repairs, because two of the diesel trucks had front end alignments done at $95 each.

Tires—The LNG trucks had a slightly higher cost per truck for tires, possibly because of more non-highway driving based on the higher number of stores per day.

Overall Maintenance Costs

Throughout the study period, the LNG trucks incurred 48% higher maintenance costs per truck than their diesel counterparts (see Figure 6). On a per-mile basis, the difference between the maintenance costs for LNG and diesel trucks is even greater, mostly because of the different usage patterns of the two sets of trucks.

The maintenance cost analysis was performed using constant dollars: the labor hour cost for maintenance was fixed at $50 per hour, and the parts costs were set using a listing of the costs as of March 31, 1999. Parts costs per truck were 74% higher for the LNG trucks. The labor hours were 20% higher for the LNG trucks.

Because the Raley's diesel trucks were used for more mileage than the LNG trucks during the year of data used for the maintenance analysis, and some maintenance was done at equal time intervals, the maintenance cost per mile for the LNG trucks has been biased higher. The LNG and diesel trucks operated as intended by Raley's and met the company's trucking needs.

Figure 5. Average maintenance cost per truck system in $

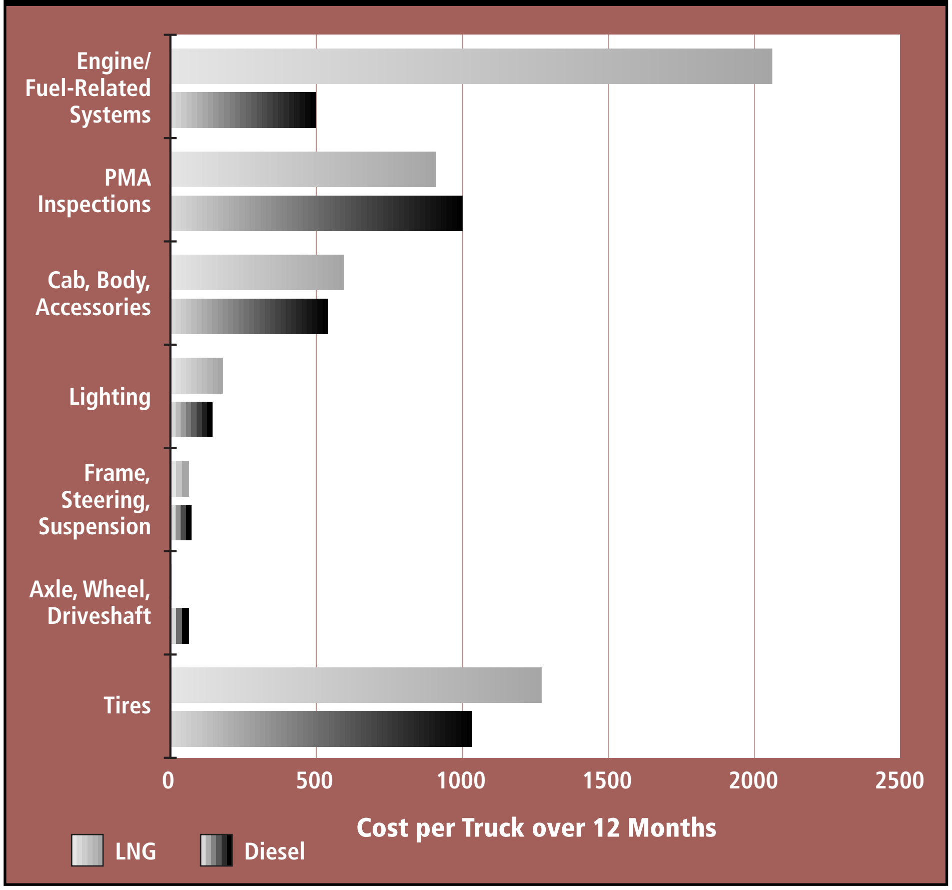


Figure 6. Total maintenance cost per truck

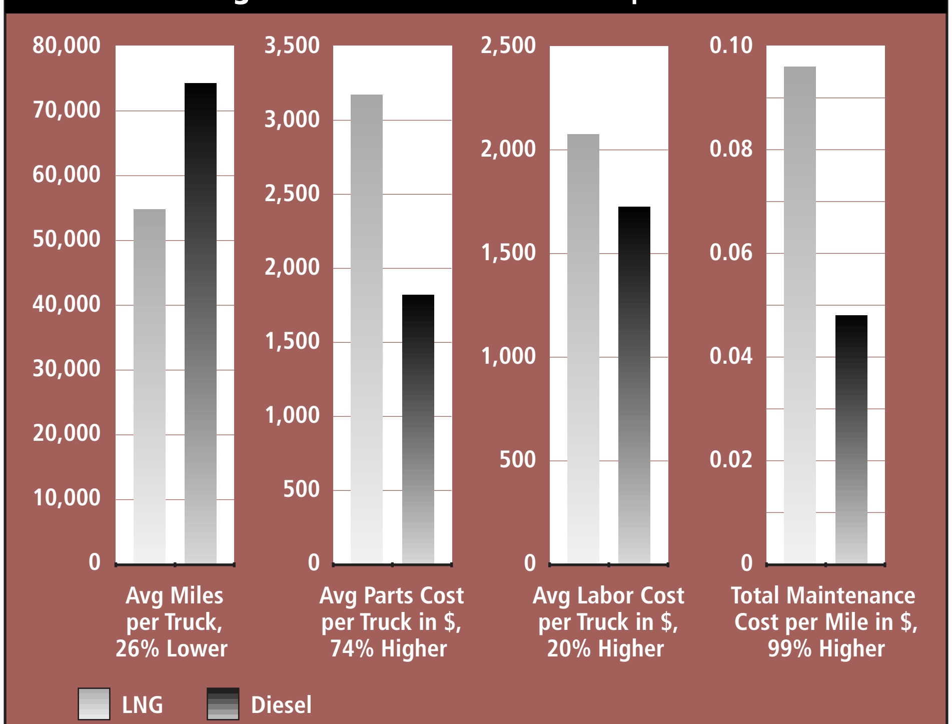


Figure 7. Overall operating costs per mile in $

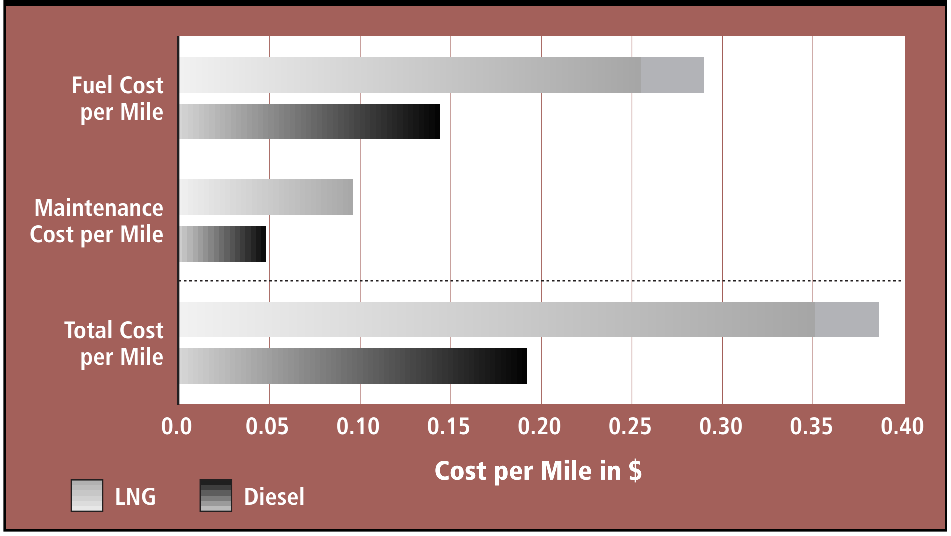
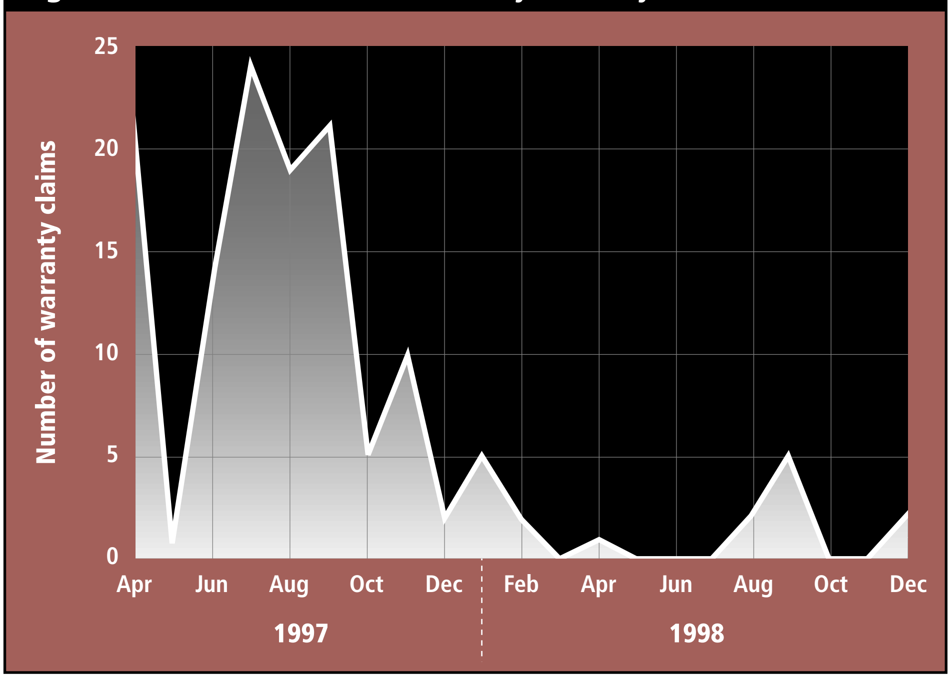


Figure 8. Number of Cummins warranty claims by month for LNG trucks



Overall Operating Costs

Overall, the eight LNG trucks cost an average of $0.383 per mile in fuel and maintenance to operate, compared to an average of $0.192 for the three diesel control trucks. Figure 7 shows the fuel and maintenance factors that contributed to the overall operating cost. Appendix A provides greater detail on the operations costs for the LNG and diesel trucks at Raley's.

In calculating the overall operating costs

- Vehicle and fueling station capital costs and driver labor are not included.
- Actual fuel costs during the study were used (as discussed on pages 15 and 16, these fuel costs are different today):
  - Diesel: $1.01 per gallon
  - LNG: $1.24 per diesel energy equivalent gallon
- Maintenance costs did not include warranty repairs paid for by the manufacturers.
- Maintenance labor cost was assumed to be $50 per hour.

These higher operating costs for the LNG trucks illustrate the importance of having low-cost LNG fuel delivered on site. A lower cost fuel would help overcome the higher operating costs for the LNG trucks. More development work continues on the natural gas engine and fuel system and will help to alleviate some of the problems experienced by Raley's.

Warranty Repair Experience and Driver Complaints

Cummins West (the local distributor for Cummins, the supplier of the diesel and LNG engines) was very supportive throughout the Raley's LNG project. Several original equipment warranty items were replaced at Cummins's expense on the LNG trucks. Early project problems included the wastegate, ignition modules,

Cost Effectiveness of Emissions Reduction at Raley's

Cleaning up emissions of NO_X and PM is necessary if clean air regulations are to be met. However, there are costs associated with cleaning up emissions. California, is willing (through the local air quality management district) to pay as much as $12,000 per ton of measurable NO_X reduction through the "Carl Moyer Program."

Emissions reductions for the Moyer Program, presented in The Carl Moyer Program Guidelines, Part II, are based on engine certification data and on a conversion factor:

- Heavy-duty line haul trucks: 2.6 bhp-h/mi
- Urban buses: 4.3 bhp-h/mi
- Other: 18.5 bhp-h/gallon of fuel used.

Only capital costs are considered in the cost of the emissions reductions, and a 10-year lifetime is assumed for heavy-duty trucks with a 5% capital recovery factor.

Although Raley's did not participate directly in the Moyer Program, information from Raley's experience can be used to develop a realistic prediction of the cost effectiveness other similar sites may expect from alternative fuel projects and emissions reductions.

Applying Raley's operating and cost data to the Moyer formula for calculating emissions reductions, and using WVU's emissions testing results (rather than engine certification data), the annual NO_X reduction per truck for the Raley's project would be:

Annual NO_X reduction =

(25.7 g/mi – 5.21 g/mi) * (53, 868 miles/yr) * (100% in CA) * (ton/907,200 g) = 1.22 tons/yr

Next, the capital cost of the trucks needs to be taken into account. The incremental cost of the LNG trucks was $35,000 each. Based on a 10-year life, this gives an annualized cost of $4,550 per year.

Overall, the potential cost effectiveness would be:

Cost effectiveness =

($4,550/yr) / (1.22 tons/yr) = $3,730/ton of NO_X.

This cost effectiveness—compared to the $12,000 per ton of NO_X reduction that the state is willing to pay for a given project—is extremely favorable for the Raley's project.

This analysis can be taken one step further by including other incremental costs for the fueling station, fuel, and maintenance. The fuel station is assumed to have a 15-year life, and the trucks are assumed to operate 53,868 miles per year (average for the LNG trucks).

Annualized Cost =

(annualized capital cost of truck + fuel station) + (incremental fuel cost) + (incremental maintenance cost) = ($4,550 + $3,360) + ($5,841) + ($2,586) = $16,337

Annualized Cost/Ton =

$16,337 / 1.22 = $13,391 / ton NO_X.

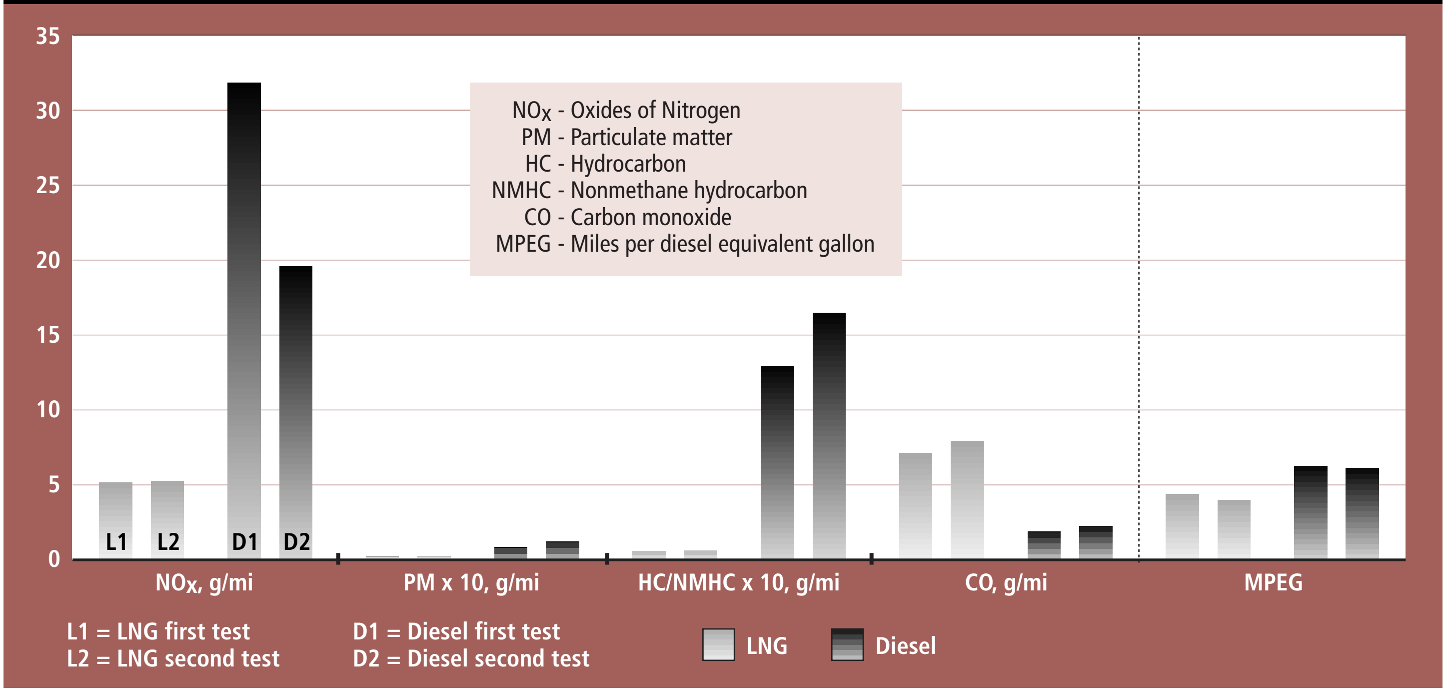
With all the incremental costs taken into account, the cost per ton of NO_X reduction is 12% higher than the $12,000 per ton of NO_X. This analysis is presented to give one perspective of the cost per unit of NO_X emission reduction, based on experience at Raley's.

and oxygen sensors. The ignition module problems in turn led to numerous spark plug, wire, and ignition coil replacements during the evaluation. As shown in Figure 8, the warranty claims dropped dramatically by the start of the fleet comparison study in December 1997. No warranty information was collected for the diesel trucks.

Driver Complaints

Driver complaints were collected on the various systems in the trucks being evaluated. These complaints were collected as part of Raley's normal practice of tracking and reporting maintenance that needed to be performed by Ozark Trucking. Complaints on engine low power

Figure 9. Emissions testing results



or rough running on the LNG trucks were the most frequently logged, with 24% of complaints concerning these issues. Many of these comments stemmed from the differences noted when drivers changed from diesel to LNG trucks. The number of these complaints decreased significantly after Cunmins made the replacements discussed above. Drivers logged complaints about the LNG fuel gauges throughout the study. The driver comments on the diesel trucks were generally fewer in number.

Emissions Testing Results

Sacramento is an Environmental Protection Agency (EPA)-designated "nonattainment area," meaning the air in parts of the Sacramento metropolitan area do not meet the National Ambient Air Quality Standards. Air quality modeling suggests that heavy-duty vehicles contribute disproportionately to NO_x and PM emissions. For example, although heavy-duty vehicles represented only about 4% of the total U.S. vehicle population in 1998, the EPA estimated that heavy-duty vehicles contributed more than 30% of the total NO_x emissions and more than 60% of the total PM emissions from on-road vehicles. For these reasons, operators of heavy-duty vehicles have been encouraged to reduce NO_x and PM from their vehicles.

The emissions tests on the LNG and diesel trucks were conducted by the WVU Department of Mechanical and Aerospace Engineering using one of its transportable heavy-duty chassis dynamometer emissions laboratories. These transportable laboratories were developed under DOE sponsorship. The emissions from the trucks were measured twice: soon after the LNG trucks went into service (July and August 1997) and again in February and March 1998. During the tests, the trucks were driven through a "5-mile route" that consisted of five acceleration-cruise-deceleration ramps. The trucks were accelerated at their maximum acceleration rate on each ramp. Each truck was driven through the 5 mile route at least three times and the emissions averaged for a single test result.

The average emission results for the diesel and LNG trucks are shown in Figure 9. The LNG trucks averaged about 80% less NO_x emissions and about 96% less PM mass emissions than the diesel trucks over both rounds of testing. This is a dramatic reduction in the emissions of highest concern for heavy-duty vehicles. The LNG trucks also emitted less nonmethane hydrocarbons compared to the hydrocarbon emissions of the diesel trucks. (Methane emissions from natural gas engines are not regulated because they are considered non-reactive in ozone formation.) In contrast, the LNG trucks emitted more carbon monoxide than the diesel control trucks. Appendix B summarizes the emissions results.

Some differences in the LNG truck results occurred between the two testing visits. This is most likely related to the changes to the engine configuration and some of the components that were upgraded as part of the warranty repairs. For the two sets of diesel testing results, the NO_x results are significantly lower for the second testing visit. This lower NO_x most likely results from engine map (calibration) and from which gears were used during the drive cycle. The continuous NO_x data suggest that an off-cycle injection timing strategy may have been at work for the diesel vehicles.

LNG Yard Tractors

As part of Raley's LNG program, two Ottawa LNG yard tractors were introduced into the fleet. Raley's uses yard tractors to move trailers around in the Distribution Center yard. Yard tractors usually do not leave the Distribution Center. They usually operate at low speed for 12 to 15 hours per day.

The drivers of the yard tractors were extremely pleased with the newer LNG yard tractors. Reasons cited by the drivers included better suspension, reduced noise and vibration, and reduced fumes. The yard tractors were equipped with Cummins B5.9G natural gas engines and used MVE, Inc. on-board LNG tanks.

The LNG yard tractors had very little downtime during the data collection period for the other LNG trucks. However, the yard tractors did have some problems with the LNG fueling process. The LNG fuel tanks on the yard tractors were smaller than the tanks on the heavy-duty LNG trucks. These smaller LNG tanks usually had high pressure when fueling was required. This high pressure in the fuel tanks was difficult for the temporary fueling system to overcome, so the tanks would need to be vent filled. This process sometimes required four or five tries to fill the tanks. The permanent LNG station has resolved this issue.

Summary and Conclusions

Based on the evaluation of the Raley's LNG truck site, we can conclude several major points:

- The LNG trucks are doing the job they were purchased to perform—pickups and deliveries in the local Sacramento area. This limited operating area was established at the request of SMAQMD to keep the emissions benefits of the trucks in the Sacramento air basin. In return, SMAQMD contributed funding to help Raley's establish LNG operations.

- The LNG trucks emitted an average of about 80% less NO_x and 96% less PM than comparable diesel trucks over WVU's 5-mile route.

- The LNG trucks had higher capital and operating costs than comparable diesel trucks. The LNG trucks were $35,000 more to purchase than the diesel trucks. The LNG trucks cost about $0.38 per mile for fuel and maintenance compared to about $0.19 per mile for the diesel trucks.

- The lower vehicle mileage for the LNG trucks caused their cost per mile for maintenance to be biased higher than expected, because the PMAs were performed on a quarterly (calendar) basis, not on a mileage basis.

- Drivers perceived the LNG trucks to be slightly underpowered for Raley's needs.

- Energy equivalent fuel economies measured in use and during emissions testing were essentially consistent. The energy equivalent fuel economy was about 38% lower for Raley's LNG trucks than for its diesel trucks. This caused some problems with range for the LNG trucks. The lower fuel economy was aggravated by unreliable fuel gauges on the LNG trucks.

- Mileage per vehicle per calendar month and year was significantly lower for the LNG trucks compared to the diesel control trucks. This lower mileage for the LNG trucks was caused by
  - Shorter routes that were closer to the Distribution Center in the Sacramento area
  - Problems with shorter operating range (miles between fuel refills) than the diesel trucks

- Operations and LNG fuel costs during the evaluation were affected by a change from a temporary to a permanent LNG fueling station at Raley's. Although there were several major delays in the construction of the permanent LNG station, its completion allowed Raley's to purchase a full tanker truckload of LNG, which reduced the cost by $0.10 per LNG gallon.

- Raley's staff indicated that their operation would benefit from an even larger LNG storage tank at the permanent fueling station (currently 13,000 gallons). The tank has reserve for vapor and liquid that cannot be used, which reduces the usable volume to about 11,500 gallons. This leaves a margin for error of 1,500 gallons when ordering fuel, representing about a 2-day supply at normal rates of fuel usage.

Fuel shipments must be scheduled carefully, or the station will either run out of fuel or will not be able to accommodate the full incoming shipment, which results in lost fuel that Raley's must pay for.

- Some problems arose with the LNG engines, such as with the wastegate, ignition modules, and calibration of the electronic control module and sensors. The LNG engine manufacturer was responsive to these problems. Operations were fairly trouble-free at the end of the evaluation.

- Raley's intends to expand its LNG truck operations; however, few choices of heavy-duty natural gas truck technologies are currently available on the market.

- As part of this project, Raley's purchased two LNG yard tractors. These vehicles have been extremely successful for Raley's. The drivers have noted that, compared to the older diesel yard tractors, the LNG yard tractors offer reduced noise and vibration as well as a welcome lack of diesel fumes.

Future LNG Operations at Raley's

Data collection for this project was completed in December 1998. Raley's planned to return the temporary QRS refueling station to Cummins West. Raley's has applied for permission to sell LNG to the public, but approval from the California Department of Weights and Measures is still pending as of March 2000.

Raley's was considering options for expanding its LNG fleet. The Cummins L10-300G engine was discontinued for new LNG purchases because of low sales volume and because the L10 was discontinued for diesel. Raley's has held discussions with Cummins West regarding a joint research project to test one or two prototype 400-hp natural gas engines. Other potential technology options to expand the fleet were Caterpillar Dual-Fuel (C10 or C12), Mack (E7G), Detroit Diesel (Series 60G), and Westport high-pressure direct injection dual-fuel technology.

On January 4, 2000, Westport Innovations, Inc., announced that the first U.S. customer for its dual-fuel natural gas/diesel system for trucks would be Raley's. The first truck is slated for delivery to Raley's late in 2000.

Contacts

Raley's Distribution Center

Stan Sasaki
Manager of Transportation
4061 Gateway Park Boulevard
Sacramento, CA 95834
Phone: (916) 928-7747
Fax: (916) 928-0761

Raley's Corporate Office

Carolyn White
Communications Manager
500 West Capitol Avenue
West Sacramento, CA 95605
Phone: (916) 373-6211
Fax: (916) 373-1587

Ozark Trucking Inc.

Ed Gamache
Fleet Maintenance Manager
900 E Street
West Sacramento, CA 95605
Phone: (916) 561-5411

SMAQMD

Tim Taylor
Director, Mobile Source Division
777 12th Street, Third Floor
Sacramento, CA 95814
Phone: (916) 874-4880
Fax: (916) 874-4899

Cummins Engine Company

Vinod Duggal
Director, Advanced Engineering,
Alternate Fuels
1900 McKinley Avenue
Columbus, IN 47201
Phone: (812) 377-7338
Fax: (812) 377-2029

Cummins West

Kevin Shanahan
President
1601 Aurora Drive
San Leandro, CA 94577
Phone: (510) 351-6101

MVE, Inc.

Dave Marohnic
Product Support Engineer
LNG Systems
407 Seventh Street NW
PO Box 234
New Prague, MN 56071-0234
Phone: (612) 882-5212

Kenworth

John Keppel
Bay Area Kenworth
425 Market Street
Oakland, CA 94607
Phone: (510) 836-6100

NREL

Paul Norton
Senior Engineer
1617 Cole Boulevard
Golden, CO 80401
Phone: (303) 275-4424
Fax: (303) 275-4415
e-mail: Paul_Norton@nrel.gov

Battelle

Kevin Chandler
Project Manager
505 King Avenue
Columbus, OH 43201
Phone: (614) 424-5127
Fax: (614) 424-5069
e-mail: chandlek@battelle.org

WVU

Nigel Clark
Department of Mechanical &
Aerospace Engineering
Morgantown, WV 26506-6106
Phone: (304) 293-3111 x2311
Fax: (304) 293-2582
e-mail: clark@cemr.wvu.edu

References and Related Reports

Battelle, August 1999, *Waste Management's LNG Truck Fleet Start-Up Experience*, NREL/BR-540-26617, Golden, CO: NREL.

Battelle, July 1999, *Raley's LNG Truck Site Final Data Report*, Columbus, OH: Battelle.

Battelle, 1998, *Dual-Fuel Truck Fleet, Start-Up Experience*, NREL/BR-540-25118, Golden, CO: NREL.

Battelle, 1998, *Project Guidelines, Alternative Fuel Truck Evaluation Project*, Columbus, OH: Battelle.

Battelle, 1997, *Raley's LNG Truck Fleet, Start-Up Experience*, NREL/BR-540-23402, Golden, CO: NREL.

Chandler, K., Norton, P., and Clark, N., 1999, "Interim Results from Alternative Fuel Truck Evaluation Project," SAE Pub. #1999-01-1505, Warrendale, PA: SAE International.

Chandler, K., Norton, P., and Clark, N., 1998, "Alternative Fuel Truck Evaluation Project: Design and Preliminary Results," SAE Paper No. 981392, Warrendale, PA: SAE International.

Clark, N., Lyons, D., Rapp, B., Gautam, M., Wang, W., Norton, P., White, C., and Chandler, K., 1998, "Emissions from Trucks and Buses Powered by Cummins L-10 Natural Gas Engines," SAE Paper No. 981393, Warrendale, PA: SAE International.

Motta, R., Norton, P., Kelly, K., Chandler, K., Schumacher, L., and Clark, N., October 1996, *Alternative Fuel Transit Buses: Final Results from the National Renewable Energy Laboratory (NREL) Vehicle Evaluation Program*, NREL/TP-425-20513, Golden, CO: NREL.

Battelle, October 1996, *Alternative Fuel Transit Buses: The Pierce Transit Success Story*, NREL/SP-425-21606, Golden, CO: NREL.

Appendix A

Fleet Summary Statistics

Fleet Summary Statistics

Table A-1. Raley's/Ozark Trucking (Sacramento, CA) Fleet Summary Statistics

Fleet Operations and Economics

	PMA 4-7 Diesel Control	PMA 4-7 LNG
Number of Vehicles	3	8
Period Used for Fuel and Oil Op Anaysis Total Number of Months in Period Fuel and Oil Analysis Base Fleet Mileage	1/98 – 12/98 12 200,961	1/98 – 12/98 12 396,118
Period Used for Maintenance Op Analysis Total Number of Months in Period Maintenance Analysis Base Fleet Mileage	6/96 – 5/97 12 222,844	1/98 – 12/98 12 438,191
Average Monthly Mileage per Vehicle Fleet Fuel Usage in Diesel #2 Equiv. Gal.	6,182 28,630	4,489 91,667
Representative Fleet MPG (energy equiv) Ratio of MPG (AF/DC)	7.02 –	4.32 0.62
Average Fuel Cost as Reported (with tax) Average Fuel Cost per Energy Equivalent Fuel Cost per Mile	1.01 per gal D2 1.01 0.144	0.74 per gal LNG 1.24 0.287
Total Scheduled Repair Cost per Mile Total Unscheduled Repair Cost per Mile Total Maintenance Cost per Mile	0.021 0.026 0.048	0.038 0.058 0.096
Total Operating Cost per Mile	**0.192**	**0.383**

Maintenance Costs

	Diesel Control	LNG
Fleet Mileage	222,844	438,191
Total Parts Cost	5,464.09	25,381.36
Total Labor Hours	103.5	331.7
Average Labor Cost (@ $50.00 per hour)	5,175.00	16,585.00
Total Maintenance Cost	10,639.09	41,966.36
Total Maintenance Cost per Truck	3,546.36	5,245.80
Total Maintenance Cost per Mile	**0.048**	**0.096**

Breakdown of Maintenance Costs by Vehicle System

	Diesel Control	LNG
Fleet Mileage	222,844	438,191
Total Engine/Fuel-Related Systems (ATA VMRS* 30, 31, 32, 33, 41, 42, 43, 44, 45)		
Parts Cost Labor Hours Average Labor Cost	1,328.30 3.4 170.00	13,103.31 67.7 3,385.00
Total Cost (for system)	1,498.30	16,488.31
Total Cost (for system) per Truck	499.43	2,061.04
Total Cost (for system) per Mile	**0.0067**	**0.0376**
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost Labor Hours Average Labor Cost	25.50 0.5 25.00	0.00 0.8 40.00
Total Cost (for system)	50.50	40.00
Total Cost (for system) per Truck	16.83	5.00
Total Cost (for system) per Mile	**0.0002**	**0.0001**
Fuel System Repairs (ATA VMRS 44)		
Parts Cost Labor Hours Average Labor Cost	446.53 1.3 65.00	1,905.58 43.2 2,160.00
Total Cost (for system)	511.53	4,065.58
Total Cost (for system) per Truck	170.51	508.20
Total Cost (for system) per Mile	**0.0023**	**0.0093**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost Labor Hours Average Labor Cost	802.50 0.6 30.00	3,760.66 8.4 420.00
Total Cost (for system)	832.50	4,180.66
Total Cost (for system) per Truck	277.50	522.58
Total Cost (for system) per Mile	**0.0037**	**0.0095**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts Cost Labor Hours Average Labor Cost	44.50 0.5 25.00	7,381.45 13.7 685.00
Total Cost (for system)	69.50	8,066.45
Total Cost (for system) per Truck	23.17	1,008.31
Total Cost (for system) per Mile	**0.0003**	**0.0184**

* American Trucking Association Vehicle Maintenance System and Repair

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Control	LNG
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost Labor Hours Average Labor Cost	0.00 0.0 0.00	0.00 0.0 0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Truck	0.00	0.00
Total Cost (for system) per Mile	**0.0000**	**0.0000**
Cooling System Repairs (ATA VMRS 42)		
Parts Cost Labor Hours Average Labor Cost	9.27 0.5 25.00	55.62 1.6 80.00
Total Cost (for system)	34.27	135.62
Total Cost (for system) per Truck	11.42	16.95
Total Cost (for system) per Mile	**0.0002**	**0.0003**
Brake System Repairs (ATA VMRS 13)		
Parts Cost Labor Hours Average Labor Cost	83.60 1.5 75.00	0.00 0.6 30.00
Total Cost (for system)	158.60	30.00
Total Cost (for system) per Truck	52.87	3.75
Total Cost (for system) per Mile	**0.0007**	**0.0001**
Transmission Repairs (ATA VMRS 26)		
Parts Cost Labor Hours Average Labor Cost	0.00 0.0 0.00	0.00 0.0 0.00
Total Cost (for system)	0.00	0.00
Total Cost (for system) per Truck	0.00	0.00
Total Cost (for system) per Mile	**0.0000**	**0.0000**
Clutch Repairs (ATA VMRS 23)		
Parts Cost Labor Hours Average Labor Cost	0.00 0.0 0.00	3.77 0.3 15.00
Total Cost (for system)	0.00	18.77
Total Cost (for system) per Truck	0.00	2.35
Total Cost (for system) per Mile	0.0000	0.0000

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Control	LNG
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost	694.31	2,211.38
Labor Hours	18.5	51.0
Average Labor Cost	925.00	2,550.00
Total Cost (for system)	1,619.31	4,761.38
Total Cost (for system) per Truck	539.77	595.17
Total Cost (for system) per Mile	**0.0073**	**0.0109**
Inspections Only—no parts replacements (101)		
Parts Cost	0.00	0.00
Labor Hours	60.0	145.6
Average Labor Cost	3,000.00	7,280.00
Total Cost (for system)	3,000.00	7,280.00
Total Cost (for system) per Truck	1,000.00	910.00
Total Cost (for system) per Mile	**0.0135**	**0.0166**
HVAC System Repairs (ATA VMRS 01)		
Parts Cost	28.47	43.12
Labor Hours	1.4	4.4
Average Labor Cost	70.00	220.00
Total Cost (for system)	98.47	263.12
Total Cost (for system) per Truck	32.82	32.89
Total Cost (for system) per Mile	**0.0004**	**0.0006**
Air System Repairs (ATA VMRS 10)		
Parts Cost	253.08	217.04
Labor Hours	1.3	15.2
Average Labor Cost	65.00	760.00
Total Cost (for system)	318.08	977.04
Total Cost (for system) per Truck	106.03	122.13
Total Cost (for system) per Mile	**0.0014**	**0.0022**
Lighting System Repairs (ATA VMRS 34)		
Parts Cost	146.01	356.76
Labor Hours	5.8	21.8
Average Labor Cost	290.00	1,090.00
Total Cost (for system)	436.01	1,446.76
Total Cost (for system) per Truck	145.34	180.85
Total Cost (for system) per Mile	**00.0020**	**0.0033**

Breakdown of Maintenance Costs by Vehicle System (concluded)

	Diesel Control	LNG
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts Cost	105.32	317.34
Labor Hours	2.3	3.7
Average Labor Cost	115.00	185.00
Total Cost (for system)	220.32	502.34
Total Cost (for system) per Truck	73.44	62.79
Total Cost (for system) per Mile	**0.0010**	**0.0011**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost	190.00	20.14
Labor Hours	0.0	0.0
Average Labor Cost	0.00	0.00
Total Cost (for system)	190.00	20.14
Total Cost (for system) per Truck	63.33	2.52
Total Cost (for system) per Mile	**0.0009**	**0.0000**
Tire Repairs (ATA VMRS 17)		
Parts Cost	2,635.00	9,108.50
Labor Hours	9.3	21.4
Average Labor Cost	465.00	1,070.00
Total Cost (for system)	3,100.00	10,178.50
Total Cost (for system) per Truck	1,033.33	1,272.31
Total Cost (for system) per Mile	**0.0139**	**0.0232**

Notes

1. The total engine/fuel-related systems were chosen to include only those vehicle systems that could be directly affected by an alternative fuel.

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

3. In general, inspections (with no part replacements) were included in the overall totals only (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 fire extinguishers, test kits, etc.; ATA VMRS 71-Body represents mostly windows and windshields.

5. Average labor cost is assumed to be $50 per hour.

6. Warranty costs are not included.

7. Diesel and LNG fuel prices shown include federal and state taxes. Diesel price is calculated as a weighted average of fuel used during the analysis period.

Appendix B

Emissions Test Results

Emissions Test Results

Table B-1. Emissions Test Results (First Test)

Emissions Summary for LNG-Powered Tractors in Sacramento, CA

Test ID	WVU Ref Num	Cycle ID	Test Date	Mileage	CO	NO_x	HC	PM	CO_2	MPG	Btu	CH_4	NMHC
973	RDC-1501-LNG-5MILES-R	5 Mile Route	7/31/97	13,600	7.60	3.06	20.55	0.06	1687	4.28	30024	18.16	0.65
974	RDC-1502-LNG-5MILES-R	5 Mile Route	8/1/97	14,000	6.64	2.88	16.52	0.04	1588	4.57	28103	14.60	0.52
975	RDC-1503-LNG-5MILES-R	5 Mile Route	8/2/97	16,400	7.83	5.57	17.22	0.06	1564	4.63	27755	15.18	0.57
968	RDC-1504-LNG-5MILES	5 Mile Route	7/25/97	17,000	7.71	12.81	14.97	0.06	1631	4.46	28799	13.05	0.57
969	RDC-1505-LNG-5MILES	5 Mile Route	7/26/97	10,800	7.16	5.00	18.41	0.09	1697	4.27	30069	16.18	0.66
970	RDC-1506-LNG-5MILES	5 Mile Route	7/28/97	15,100	6.82	4.50	15.48	0.05	1627	4.48	28729	13.60	0.56
971	RDC-1507-LNG-5MILES	5 Mile Route	7/29/97	14,800	6.58	3.65	18.31	0.07	1700	4.27	30100	16.13	0.62
972	RDC-1508-LNG-5MILES	5 Mile Route	7/30/97	16,500	6.60	3.79	18.64	0.09	1765	4.12	31222	16.42	0.64
			Average:	**14,800**	**7.12**	**5.16**	**17.51**	**0.07**	**1657**	**4.39**	**29350**	**15.41**	**0.60**

Emission Summary for Diesel-Powered Tractors in Sacramento, CA

Test ID	WVU Ref Num	Cycle ID	Test Date	Mileage	CO	NO_x	HC	PM	CO_2	MPG	Btu
976	RDC-1586-D2-5MILES-R2	5 Mile Route	8/4/97	160,900	2.02	28.46	1.56	1.34	1548	6.54	19880
978	RDC-1592-D2-5MILES-R	5 Mile Route	8/7/97	132,900	1.96	35.18	1.28	0.75	1688	6.01	21652
977	RDC-1593-D2-5MILES-R	5 Mile Route	8/6/97	166,900	1.67	31.85	1.04	0.42	1624	6.24	20822
			Average:	**153,600**	**1.88**	**31.83**	**1.29**	**0.84**	**1620**	**6.26**	**20785**

Table B-2. Emissions Test Results (Second Test)

Emissions Summary for LNG-Powered Tractors in Sacramento, CA

Test ID	WVU Ref Num	Cycle ID	Test Date	Mileage	CO	NO_x	HC	PM	CO_2	MPG	Btu	CH_4	NMHC
1058	RDC-1501-LNG-5MILES-R	5 Mile Route	2/28/98	38,000	9.42	4.36	19.63	0.033	2019	3.60	35686	17.31	0.66
1048	RDC-1502-LNG-5MILES	5 Mile Route	2/20/98	38,600	8.44	4.65	25.49	0.041	1816	3.96	32469	22.69	0.63
1052	RDC-1503-LNG-5MILES	5 Mile Route	2/24/98	46,000	7.95	7.93	16.14	0.047	1633	4.45	28891	14.36	0.60
1056	RDC-1504-LNG-5MILES-R2	5 Mile Route	2/26/98	51,600	8.27	4.59	39.27	0.049	1823	3.91	32861	35.20	0.74
1057	RDC-1505-LNG-5MILES	5 Mile Route	2/27/98	28,800	8.95	7.08	17.47	0.037	1981	3.68	34935	15.60	0.67
1054	RDC-1506-LNG-5MILES	5 Mile Route	2/25/98	44,700	6.95	4.42	17.54	0.035	1841	3.96	32492	15.53	0.53
1053	RDC-1507-LNG-5MILES	5 Mile Route	2/24/98	46,000	6.51	5.42	15.97	0.025	1688	4.32	29784	14.12	0.50
1055	RDC-1508-LNG-5MILES	5 Mile Route	2/25/98	52,700	6.90	3.56	19.48	0.057	1764	4.11	31260	17.16	0.67
			Average:	**43,300**	**7.92**	**5.25**	**21.37**	**0.040**	**1821**	**4.00**	**32297**	**19.00**	**0.62**

Emission Summary for Diesel-Powered Tractors in Sacramento, CA

Test ID	WVU Ref Num	Cycle ID	Test Date	Mileage	CO	NO_x	HC	PM	CO_2	MPG	Btu
1059	RDC-1586-D2-5MILES	5 Mile Route	3/2/98	205,700	2.32	20.79	1.95	1.77	1654	6.12	21262
1060	RDC-1592-D2-5MILES	5 Mile Route	3/3/98	174,000	2.16	20.85	1.65	1.17	1629	6.22	20919
1061	RDC-1593-D2-5MILES	5 Mile Route	3/4/98	209,200	2.30	17.14	1.50	0.72	1692	5.99	21718
			Average:	**196,300**	**2.26**	**19.59**	**1.70**	**1.22**	**1658**	**6.11**	**21299**

Produced by the

Center for Transportation Technologies and Systems at the National Renewable Energy Laboratory (NREL), a U.S. Department of Energy national laboratory

NREL
1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL/BR-540-27678
May 2000

Printed with a renewable-source ink on paper containing at least 50% wastepaper, including 20% postconsumer waste