Waste Management'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

WASTE MANAGEMENT'S LNG TRUCK FLEET: FINAL RESULTS

Alternative Fuel Truck Evaluation Project

by

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Table of Contents

Executive Summary

Waste Management, Inc., a private company based in Houston, Texas, began operating a fleet of heavy-duty refuse trucks powered by liquefied natural gas (LNG) at its Washington, Pennsylvania, facility in 1997. Waste Management currently operates seven LNG refuse trucks at that site.

The U.S. Department of Energy (DOE) Office of Heavy Vehicle Technologies sponsored a research project to collect and analyze data on the performance and operation costs of five of Waste Management's LNG trucks in commercial service, for comparison with data on the performance of three diesel trucks operating on similar routes.

This report presents an evaluation of five of the first seven LNG trucks produced by Mack. Mack partnered with Waste Management in Washington, Pennsylvania, to field test its natural gas engine design and gain experience.

Objective

The objective of the DOE research project, managed by the National Renewable Energy Laboratory, 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.

This information should benefit decision makers by providing a real-world account of the obstacles overcome and the lessons learned in adapting alternative fuel trucks to a hauling site previously geared toward diesel trucks.

Methods

Data were gathered daily from fuel and maintenance tracking systems for more than one year. The data parameters included

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

In general, these data were already collected as part of normal business operations at the Waste Management site in Washington, Pennsylvania.

Results

The results shown in this report are based on an evaluation of the first Mack LNG trucks placed in service by Mack and Waste Management in Washington, Pennsylvania. Start-up problems were encountered that have been resolved. Although this implementation was considered successful by both Mack and Waste Management, sites using new Mack LNG refuse trucks (as of model year 2000) should expect significantly lower operating costs than experienced in Washington, Pennsylvania.

- Throughout the evaluation period, both the LNG and the diesel fleets did the work Waste Management expected. The major difference in operations was that the monthly average mileage (miles driven) per truck was 26% lower for the LNG trucks.

- Drivers and refuse workers have reported that there is no difference in power between the LNG and diesel trucks. The refuse workers prefer the LNG trucks because of their lack of diesel odor and quieter operation.

- Diesel equivalent fuel economy was 27% lower for the LNG trucks for in-use operation during the evaluation. ("Diesel equivalent" or "energy equivalent" comparisons allow fuels with different energy content, such as diesel fuel and LNG, to be evaluated on the same terms. See box on page 15 for more information.) Diesel equivalent fuel consumption per engine hour was only 4% higher for the LNG trucks. However, these values must be interpreted in light of the fact that the LNG trucks were used 26% fewer miles and 3% fewer engine hours. The LNG trucks also were used to haul 34% more refuse by weight.

  The more representative fuel economy results came from the emissions testing and the controlled fuel economy test with the same load on the vehicles and essentially the same route and average speed. Fuel economy measured during the emissions testing showed that the LNG trucks had a 9% to 12% lower fuel economy. This fuel economy result shows considerable improvement compared to other heavy-duty natural gas engine products.

- The per-engine-hour fuel cost per mile from the evaluation was double for the LNG trucks and 54% higher for the LNG trucks. These high costs were caused by the high price paid in Washington, Pennsylvania, for LNG—\$0.88 per LNG gallon or \$1.77 per diesel equivalent gallon with taxes. Diesel fuel price used for the evaluation was \$1.20 per gallon.

  In some other parts of the country, LNG costs about \$0.50 per LNG gallon, (\$1.13 per diesel equivalent gallon with taxes). Based on the evaluation results from Washington, Pennsylvania, if LNG were \$1.13 per diesel equivalent gallon and diesel were \$1.50 per gallon, the LNG per-mile truck fuel costs would be 3% higher; engine-hour costs would be 21% lower.

- The LNG trucks had per-mile maintenance costs that were 63% higher and per-engine-hour costs 23% higher. The maintenance costs for the LNG trucks reflect extra effort by the Waste Management staff to understand and troubleshoot the LNG trucks. This extra effort also includes labor to support Mack in its troubleshooting effort and refinements for the final Mack natural gas refuse truck product. Also, these costs were higher because Mack required preventive maintenance twice as often for the LNG trucks. Beginning with the 2000 model year, the preventive maintenance cycle is the same as for diesel: 600 engine hours. Mack is considering increasing the maintenance interval for the LNG trucks by 50% to 900 engine hours. This increase is expected to significantly reduce maintenance costs for the LNG trucks.

- Overall, the LNG trucks cost 80% more to operate per mile and 37% more per engine hour, excluding driver labor. Operating costs were affected by differences in miles traveled between the fleets, the high cost of the LNG fuel, and by differences in the weight of refuse carried per fleet, all of which favored the diesel trucks.

- Emissions results from testing on a portable chassis dynamometer using two duty cycles showed much lower particulate matter emissions for the LNG trucks. The non-methane hydrocarbon emissions for the LNG trucks were much lower than the total hydrocarbon emissions for the diesel trucks.

  Three of the LNG trucks had a problem with the turbocharger. For new model year 2000 LNG trucks, Mack uses a different turbocharger manufacturer. The three LNG trucks affected by a turbocharger problem are not included in the nitrogen oxide (NO_x) emissions comparison. The LNG trucks had 16% lower NO_x than the diesel trucks on the Central Business District cycle and 32% lower NO_x than the diesel trucks on the Waste Management cycle.

The engines used during the evaluation were not emissions certified, but the engine calibration was the same used for emissions certification. Improvements in control and operation of the natural gas engine were implemented in production engines sold by Mack during model year 2000.

- The LNG fuel station was installed with the storage tank underground. It is reported to operate well. Minor problems have been reported with the fuel nozzle.

Lessons Learned

This LNG truck project provided Waste Management, DOE, and other participants the opportunity to learn many lessons about implementing alternative fuels, including

- Communication, commitment, and training are essential.
- The project must have a committed champion or nucleus of support to succeed.
- Drivers need a contact person who can handle questions or problems. Drivers may sense that something is wrong with the vehicles; but because the technology is new, they may not know whether the problems are real.
- Creative troubleshooting is essential.

Obstacles Overcome

Waste Management reported several in-service failures and changes to the trucks during the process of converting the LNG trucks from operating prototypes into nearly full production vehicles. The components changed or repaired on the LNG vehicles include electric module, contaminated fuel line, blocked exhaust back pressure line, leaking fuel nipple at fuel tank, fuel level sensors, and accelerator pedal.

Since August 1998, a few more problems, such as fuel tank gauges, fuel valve adjustments, fuel regulators, spark plugs, and ignition coils, occurred with the LNG fleet. All were resolved.

Future LNG Operations at Waste Management

Waste Management remains committed to natural gas as a heavy-duty trucking fuel.

Waste Management, in concert with alternative fuel project partners, is developing an on-site small-scale liquefaction capability. This will use natural gas from the Columbia Gas pipeline. Landfill gas may also be used as the feedstock for the LNG in the future. This should make the fuel cost much more reasonable and allow the LNG fleet to expand.

Based on the positive experience in Washington, Pennsylvania, Waste Management is currently implementing alternative fuels at several other operating sites. During the next two years, Waste Management plans to deploy approximately 200 LNG refuse collection trucks in locations throughout California.

Natural Gas Trucks from Mack

This LNG refuse truck demonstration at Waste Management in Washington, Pennsylvania, has successfully brought the Mack LNG refuse truck from prototype to production for model year 2000. Mack accomplished several goals during this project:

- During the demonstration, Mack certified the E7G Eco-Tech engine below

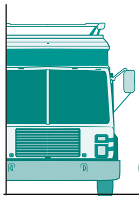
2.5 g/bhp-hr NO_x for 325-hp and 350-hp settings for the U.S. Environmental Protection Agency and California Air Resources Board.

- Mack demonstrated a significant improvement in fuel economy for heavy-duty natural gas engines. The fuel economy testing as part of the emissions testing showed that the natural gas trucks had an energy equivalent fuel economy 9% to 12% lower than the comparable diesel trucks on a slow average speed cycle (10 to 12 mph). Previous experience for heavy-duty natural gas engines showed an energy equivalent fuel economy of 25% to 35% below diesel.

- Mack worked out the logistics of assembling the LNG trucks on the same production line as the diesel trucks at the Macungie plant. An LNG truck is a standard product for the two refuse truck models (MR and LE).

- Mack has started to respond to significant interest in purchasing natural gas refuse trucks.

- Mack is engineering the CH tractor to use LNG and operate on the 350-hp E7G Eco-Tech engine based on the experience from the refuse trucks. Mack plans to release the CH model using the natural gas E7G engine uprated to higher than 400 hp and available in July 2001.



Overview

Waste Management, Inc., based in Houston, Texas, is the largest waste management service company in North America. It employs approximately 60,000 persons and has more than 1,400 refuse collection facilities.

At its 143-truck facility in Washington, Pennsylvania (south of Pittsburgh), Waste Management has operated heavy-duty refuse trucks fueled by liquefied natural gas (LNG) since August 1997. The company's fleet now includes seven LNG Mack trucks with E7G engines.

Between November 1998 and May 2000, data on selected LNG and diesel trucks from Waste Management were collected for evaluation as part of the U.S. Department of Energy (DOE)/ National Renewable Energy Laboratory (NREL) Alternative Fuel Truck Evaluation Project.

The purpose of this report is to provide transportation professionals with summary 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, the report should benefit decision makers by providing a real-world account of the obstacles overcome and the lessons 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 summarizes the results of the LNG study at Waste Management. Further technical background, research methods, extensive original data, and detailed discussions are presented in a companion document (*Waste Management Final Data Report, NREL,* August 2000).

Alternative Fuel Projects at DOE and NREL

NREL, a DOE national laboratory, managed the data collection, analysis, and reporting activities for the Waste Management LNG truck evaluation on behalf of DOE.

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

- Fleet managers can make informed decisions when purchasing AFVs.
- AFVs 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.

Alternative fuels evaluated by NREL and participating companies across the United States include LNG, CNG, biodiesel, ethanol, methanol, and propane (liquefied petroleum gas).

The Alternative Fuel 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. Specifically, the program seeks to provide comprehensive, unbiased evaluations of the newest generation of alternative fuel engine and vehicle technologies.

Heavy-duty alternative fuel trucks have been evaluated across the United States through data collection and analysis since 1996. The truck program includes five demonstration sites and continues to add new sites. Other evaluation sites include

- Raley's (Sacramento, California)
- Orange County Sanitation District (Fountain Valley, California)
- United Parcel Service (Hartford, Connecticut)
- Ralphs Grocery (Riverside, California)

Sites have been selected according to the kinds of alternative fuel technology in use, the types of trucks and engines, the availability of diesel comparison ("control") vehicles, and the host sites' interest in using alternative fuels.

The data collection and evaluation efforts are subject to peer review and DOE approval. The results of the evaluation at each site are being published separately.

Host Site Profile: Waste Management, Inc., in Washington, Pennsylvania

The participating host site for this study was the Washington, Pennsylvania, facility of Waste Management, Inc., a private refuse hauling and waste management services company based in Houston, Texas. Waste Management operates LNG and diesel trucks in refuse collection across a five-county operating area in and around Washington.

Waste Management's LNG Trucks

The first of the seven LNG trucks ordered from Mack Trucks, Inc., was delivered to Washington, Pennsylvania, in the spring of 1997, and started operation the following August. Six more LNG trucks were introduced into the fleet over the next two years.

Waste Management's LNG trucks operate on the same duty cycle as the rest of the fleet, which is daily city and suburban refuse pickup service. The fleet services 900 to 1,000 houses per day.

Six of the LNG trucks are MR model trucks, and data from five are included in the analysis. One LNG truck is an LE model and is not included because the truck systems are different from those of the MRs. The other LNG truck not included is the newest MR model truck, which started operation at the end of July 1999. The data collected for this vehicle were insufficient for analysis. Operating information from these two LNG trucks is presented separately in the appendixes of the *Final Data Report.*

Mack partnered with Waste Management to field test Mack's natural gas engine design and gain experience. The engines used were not emissions certified; however, the engine calibration on the test vehicles was the same used for emissions certification.

Some improvements in control and operation of the natural gas engine were implemented in production engines sold by Mack during model year 2000.

Another aspect of Waste Management's partnership with Mack relates to warranty costs. Maintenance costs for the LNG trucks included mechanic labor for troubleshooting engine and fuel system problems that normally would have been covered under warranty, at no expense to the fleet operator. Waste Management and Mack agreed to this arrangement to move the LNG trucks from development to production more quickly.

The arrangement was very successful in keeping the trucks on the road and achieving improved performance. However, it also drove the maintenance costs for the LNG trucks higher.

For this reason, maintenance costs for production LNG vehicles being sold by Mack outside the scope of this evaluation should be significantly lower than those for these first trucks at Waste Management.

As shown in Table 1, the five LNG trucks evaluated were model years 1997 through 1999 Mack MR trucks equipped with Mack E7G engines. The three diesel trucks used for comparison were all model year 1997 Mack MR trucks equipped with Mack E7 engines.

Table 1. Vehicle System Descriptions

Description	Diesel Control	LNG
Chassis Manufacturer/Model	Mack MR Refuse	Mack MR Refuse
Chassis Model Year	1997	1997, 1998, 1999
Engine Manufacturer/Model	Mack E7 - 300	Mack E7G - 325
Engine Ratings Max. Horsepower Max. Torque	 300 hp @ 1950 rpm 1080 lb-ft @ 1200 rpm	 325 hp @ 1950 rpm 1180 lb-ft @ 1250 rpm
Fuel System Storage Capacity	72 gallons	150 LNG gallons usable (90 diesel equivalent gallons) — 2 LNG tanks from MVE, Inc.
Transmission Manufacturer/Model	Allison HT740RS, 4-speed automatic	Allison HT740RS, 4-speed automatic
Catalytic Converter Used (Y/N)	No	No
Packer Body Manufacturer	Leach	EZ Pack, Leach
Vehicle Cost in Comparison to Diesel	Baseline	+$40,000

Courtesy of Kevin Chandler/PIX 09567

Figure 1. LNG truck at Waste Management, Washington, Pennsylvania

The LNG trucks have a slightly higher peak torque and peak horsepower rating than the diesel trucks. All the LNG trucks had the same engine calibration, which was updated during July 1998.

The different years of manufacture and different dates for start of operation were addressed by collecting all back maintenance data for the older diesel trucks. As discussed later, this allows similar vehicle lifetimes for the study fleets to be compared.

Each LNG truck cost about $40,000 more than an equivalent diesel refuse truck. Waste Management installed the packer body and a tag axle on the first four LNG trucks after delivery from Mack. For the last three LNG trucks, Mack installed the tag axle and Waste Management installed only the packer body. Figure 1 shows an LNG refuse truck at Waste Management.

Waste Management's drivers, who received specialized training in fueling and safety for the new technology, came to prefer the LNG trucks, because they have no diesel smoke or smell, are quieter, and have more power than the diesel trucks (325 hp versus 300 hp for the comparable diesel trucks).

Waste Management's Involvement in Air Quality Improvement

In 1991, Chambers Development Company (later William H. Martin, Inc., and now Waste Management, Inc.) began exploring the possibility of using the site's landfill as an energy source to fuel its refuse trucks. Landfill gas (LFG) could be converted to usable natural gas fuel, but the technology at that time did not produce acceptable quality fuel. Further analysis of the fuel processing and engine requirements showed that LFG conversion did not suit the site at that time.

A strong commitment to finding an alternative to diesel fuel for environmental and economic reasons led Waste Management to explore on-site natural gas fueling, with the hope of expanding to LFG conversion in the future. A working group of government funding sources and industry participants was formed to develop a natural gas-fueled refuse truck and to provide on-site LNG fueling at the Washington, Pennsylvania, site. Partners included

- Waste Management, Inc.
- Mack Trucks, Inc.
- Gas Technology Institute (GTI, formerly Gas Research Institute)
- DOE/NREL
- Pennsylvania Department of Environmental Protection
- Southwest Research Institute (SwRI)
- Columbia Gas of Pennsylvania
- Chart Industries (formerly CVI, Inc.)
- American Trucking Associations/ Trucking Research Institute

Mack, supported by SwRI, built a production natural gas truck in 1995. The first LNG truck for Waste Management went into service in August 1997. To support the LNG truck development, GTI and CVI, Inc., led the effort to develop and install an on-site LNG fueling station at Washington, Pennsylvania. This was the first underground LNG fueling station in the United States. It was ready for operation in mid-1997.

Project Design and Data Collection

Data were gathered from Waste Management's fuel and maintenance tracking systems daily. The data parameters included

- Diesel fuel consumption by vehicle and fill
- LNG fuel consumption by vehicle and fill
- Mileage and engine hour 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., roadcalls)
- Records of repairs covered by manufacturer warranty

The data collection was designed to cause as little disruption for Waste Management as possible. Data were sent from the site to an NREL contractor for analysis. In general, staff at Waste Management sent copies (electronic and/or paper) of data that had already been collected as part of normal business operations.

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

The study design included the tracking of safety incidents affecting the vehicles or occurring at the fueling station or in the maintenance facilities. No reportable safety incidents occurred during the data collection period.

Waste Management's Facilities and Bulk Fuel Storage

Waste Management operates 143 refuse hauling trucks over a five-county service area in the Washington, Pennsylvania, area. The truck operations facility covers 10 acres and employs a staff of more than 250.

Fuel for the LNG trucks is provided by a permanent station equipped with an underground 13,000-gallon storage tank (manufactured and installed by Chart Cryogenic Components Division, see Figure 2). The fueling station includes a pump that can fill a warm vehicle tank without venting. The dispenser can provide as much as 30 gallons of LNG per minute.

The station uses on-the-fly conditioning that allows the station storage tank to operate at lower pressure. The vacuum-insulated dispensing hose is counterbalanced so the nozzle stays off the ground when not in use.

The cost to construct and install the LNG fueling station was about \$500,000. The capability to provide compressed natural gas (CNG) at 3,600 psi was added to the LNG fueling station at the end of 1999. The facility converts LNG to compressed natural gas (LCNG). The added components were a larger heat exchanger and an additional cryogenic pump along with changes to the computer control software. Chart Industries reported that this fuel station would cost \$700,000 to \$750,000 today in its current configuration.

PIX 09570/Kevin Chandler

Figure 2. **LNG fueling station with added LCNG components**

The LNG fueling station had problems with the dispensing nozzle, including fuel leakage during filling, which causes ice buildup on the nozzle and on the seal. This can make connecting and disconnecting the nozzle at the truck fuel tank difficult and damages the seal on the nozzle. A modified design JC Carter nozzle is now being used and seems to control leaks better.

The only other problem reported was damage to the dispenser readout caused by a lightning strike toward the end of summer 1999.

Fuel for the diesel trucks is provided by an aboveground 10,000-gallon diesel storage tank (see Figure 3).

The maintenance facility (Figure 4) was built at about the same time the LNG program started (early 1997). It has two bays equipped with methane gas and heat detectors as well as audible and visual alarm systems (manufactured by

Figure 3. **Diesel fueling station with maintenance facility in background**

Figure 4. **Maintenance facility**

Honeywell) in case of a natural gas fuel leak. The cost for this system was not separated from the cost of constructing the new maintenance facility. The trucks are parked outside when not being driven or serviced.

Project Start-Up at Waste Management

As noted earlier, the first LNG trucks from Mack began operation in Washington, Pennsylvania, in August 1997. Waste Management agreed to do most of the warranty work without reimbursement from Mack. The mechanics have learned to troubleshoot and service the trucks with much less involvement from the manufacturer compared to other alternative fuel operations or other new technology development projects.

Nevertheless, Waste Management personnel have benefited from the support of Mack's technical know-how in ensuring the success of the LNG project. Mack has been extremely responsive to Waste Management's needs to make changes to the LNG trucks and provides parts on short notice.

There were several in-service failures and changes to the trucks during the process of converting the LNG trucks from operating prototypes into nearly full production vehicles. The following components were changed or repaired on the LNG vehicles through July 1998:

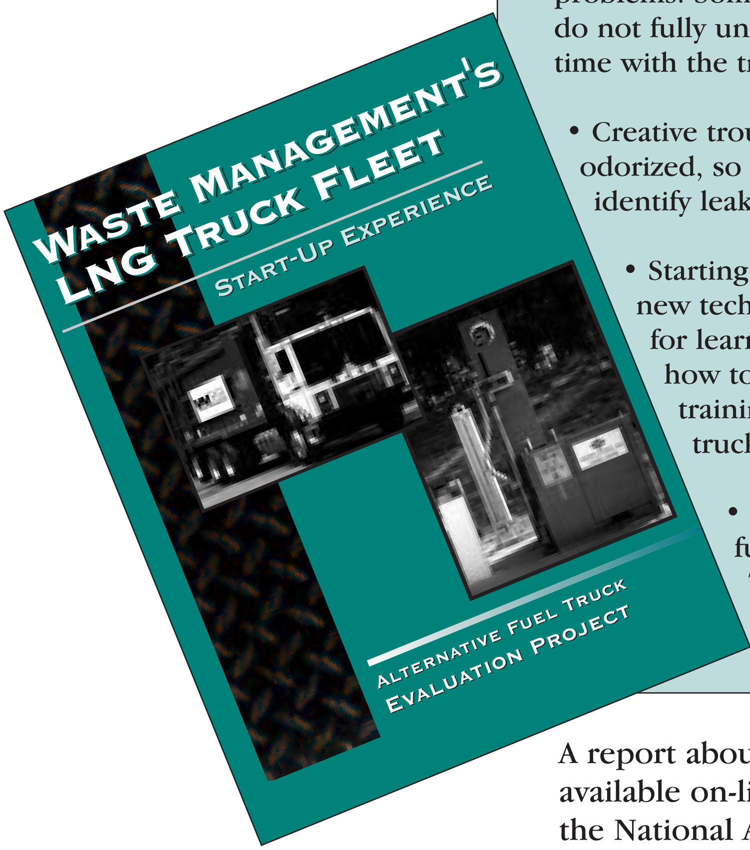
- Electric module
- Contaminated fuel line
- Blocked exhaust back pressure line
- Leaking fuel nipple at fuel tank
- Fuel level sensors
- Accelerator pedal
- Methane detector
- Wastegate actuator
- Engine control unit chip calibration
- Turbocharger

Since the "clean point" for the data collection and evaluation (August 1, 1998), a few more problems have occurred with the LNG fleet, all of which were resolved:

- All LNG trucks
  - Repaired the fuel tank gauges
  - Added humidity sensors for the engines
  - Replaced the accelerator pedals with a new design
- Isolated failures
  - Adjusted fuel valves on five LNG trucks
  - Replaced two fuel regulators
  - Replaced spark plugs on five LNG trucks
  - Replaced eight ignition coils
  - Repaired a broken wire in a harness

Lessons Learned at Start-Up

- Communication, commitment, and training are essential.
- The project must have a committed champion or a nucleus of support to succeed. This will ensure that the project, whether large or small, will receive enough attention to start-up issues such as fueling infrastructure and training.
- Recognize that the LNG trucks will not mix immediately with the diesel fleet. There can be differences between the systems, but a troubleshooter who knows the engines can resolve many problems.
- Drivers need to have a contact who can handle questions or problems. Sometimes drivers sense that something is wrong but do not fully understand the new technology. They spend more time with the trucks than anyone else, and their input is valuable.
- Creative troubleshooting is essential. For example, LNG is not odorized, so Mack used a portable methane detector to help identify leaks.
- Starting with a few trucks is the best way to introduce new technology into a fleet operation. This gives time for learning about the new technology and for learning how to integrate the trucks into normal operations and training. However, to capture economies of scale, more trucks can equate to more savings in operating costs.
- Carefully plan the timing of delivery of the fuel infrastructure and the delivery of the trucks. The installation of the fuel infrastructure may have delays; plan some time into the schedule for these potential delays.



A report about Waste Management's start-up experience is available on-line at www.ott.doe.gov/heavy_vehicle or from the National Alternative Fuels Hotline at 800/423-1DOE.

Evaluation Results

The analyses in this report cover five LNG trucks and three diesel trucks operating during the 12-month focus periods (see Table 2). These periods were chosen to analyze each vehicle over a similar range of accumulated mileage.

Actual Truck Use in Refuse Hauling Service

The LNG and diesel fleets were used for residential refuse pickup 5 to 6 days per week, on one route per day. Each truck collected refuse and returned to the landfill for unloading. Unloading was required more than once per day during peak times of the year.

Throughout the evaluation period, both the LNG and the diesel fleets did the work Waste Management expected. The major difference in operations was that the monthly average mileage (miles driven) per truck was 26% lower for the LNG trucks.

Table 2. Evaluation Vehicles and Data Evaluation Periods

	Truck	Start Date	Maintenance Start Mileage	Fuel Data Period	Maintenance Data
Diesel	300242	2/17/97	12403	11/98 – 10/99	8/97 – 7/98
Diesel	300237	7/9/97	16186	11/98 – 10/99	1/98 – 12/98
Diesel	300239	8/25/97	10709	11/98 – 10/99	2/98 – 1/99
LNG	300243	8/19/97	24409	11/98 – 10/99	11/98 – 10/99
LNG	300241	4/16/98	11853	11/98 – 10/99	11/98 – 10/99
LNG	300240	6/3/98	8554	11/98 – 10/99	11/98 – 10/99
LNG	303352	4/28/99	2365	5/99 – 10/99	6/99 – 5/00
LNG	303351	5/18/99	812	5/99 – 10/99	6/99 – 5/00

During the evaluation, Waste Management staff were concerned that the LNG trucks might not have the range of the diesel trucks. However, the difference in range of the LNG and diesel trucks based on the fuel economy testing on a simulated Waste Management cycle (during emissions testing) showed that the range was 10% higher for the LNG trucks when operated in the same service (245 miles for LNG versus 222 miles for diesel). Waste Management staff also wanted the LNG trucks closer to the maintenance facility in case of operating problems.

The diesel trucks generally traveled farther from their base of operations. Consequently, the diesel trucks had higher mileage per month and a higher average speed than the LNG trucks.

Figure 5 shows the monthly average miles traveled and engine hours of operation for the diesel and LNG fleets. The LNG trucks averaged 1,688 miles per month; the diesel trucks averaged 2,295 miles per month. Figure 6 shows the average monthly miles driven per truck.

Refuse industry fleet operators generally base most of their fleet statistics on engine hours rather than on miles driven. Because refuse trucks tend to have a very low average speed, fuel comsumption and preventive maintenance schedules are usually based on engine hours of operation.

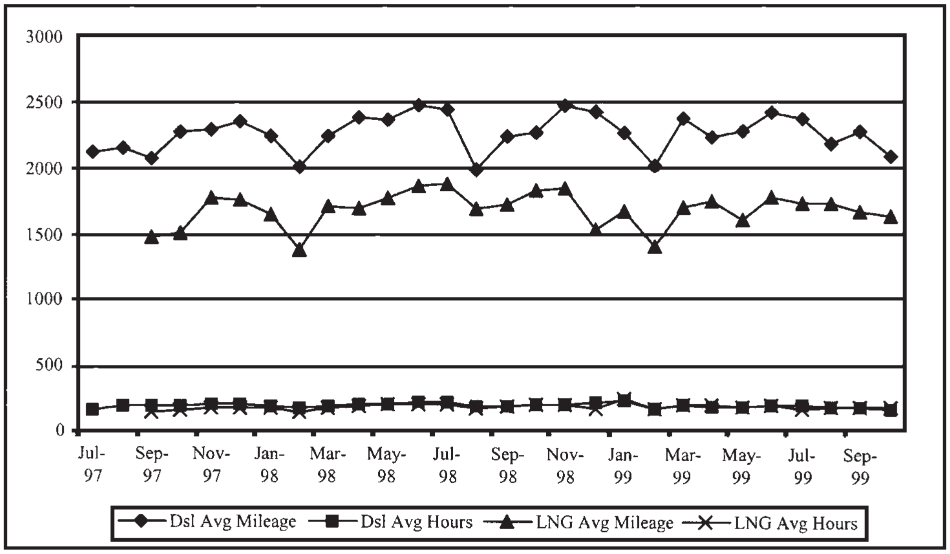
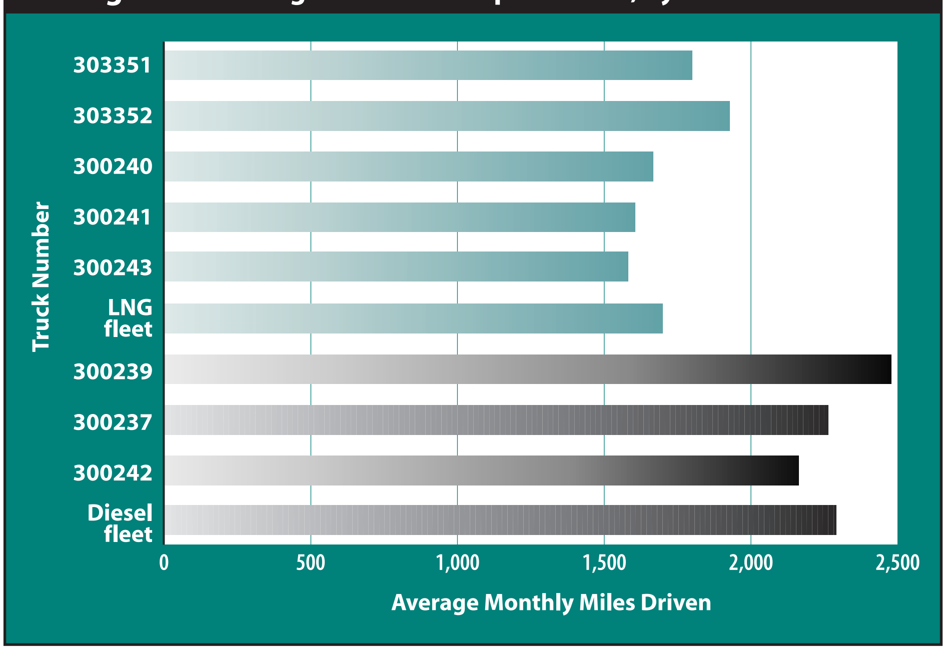


Figure 5. Monthly average mileage and engine hours

Figure 6. Average miles driven per month, by truck and fleet



Waste Management's LNG trucks averaged 8.7 mph throughout the evaluation period; its diesel trucks averaged 11.5 mph.

On a given day of operation, the trucks' engines run the entire time the driver is working (7 to 12 hours per day). For this report, all vehicle usage, fuel economy and costs, and maintenance costs are analyzed separately based on mileage and then based on engine hours. The monthly average miles driven per truck were 26% lower for the LNG trucks, but the monthly average engine hours per truck were only 3% lower for the LNG trucks (see Figure 5).

One other difference was that the LNG trucks were used to haul 34% more refuse by weight each day. This had a significant effect on fuel consumption.

Fuel Economy and Maintenance Costs

Diesel equivalent fuel economy per mile driven was 27% lower for the LNG trucks for in-use operation. Fuel consumption calculated per engine hour was 4% higher for the LNG trucks. The LNG trucks had significantly higher maintenance costs: 63% higher per mile and 23% higher per engine hour. Details of these and other costs follow.

Fuel Economy

Each LNG truck used an average of 74 gallons of LNG per day of operation (45 gallons diesel equivalent). Each diesel control truck used an average of 35 gallons of diesel fuel per day of operation.

Figure 7 shows the fleet averages by month in miles per diesel equivalent gallon and in diesel equivalent gallons per hour. Figure 8 compares per-truck and overall fleet fuel economy based on mileage; Figure 9 shows the comparison based on engine hours.

Diesel equivalent gallons are calculated based on a standard LNG gallon divided by 1.67 (the conversion factor for pure methane; LNG at this site is essentially methane, based on discussions with the fuel supplier, ALT-USA). The fuel consumption expressed in energy equivalent gallons per hour is 4% higher for the LNG trucks compared to the diesel trucks.

The average speeds (see Table 3) put the miles per diesel equivalent gallon numbers for LNG and diesel trucks into perspective. The average speeds for the LNG and diesel trucks are low (8.7 to 11.5 mph), but the LNG trucks' average speed was 24% lower than that of the diesel trucks. This difference has a significant impact on the efficiency of the spark-ignited LNG engines. Also, the heavier load contributed to the lower fuel economy for the LNG trucks.

In general, historical experience has shown that the diesel equivalent fuel economy is usually 15% to 30% lower for the LNG trucks. In-use data at Waste Management appear to be consistent with previous experience, showing a miles-per-gallon/equivalent-gallon fuel economy 27% lower for the LNG trucks than for the diesel trucks. However, this comparison involved significant duty cycle differences between the diesel and LNG trucks. The controlled fuel economy testing from the emissions testing is a much better comparison to consider.

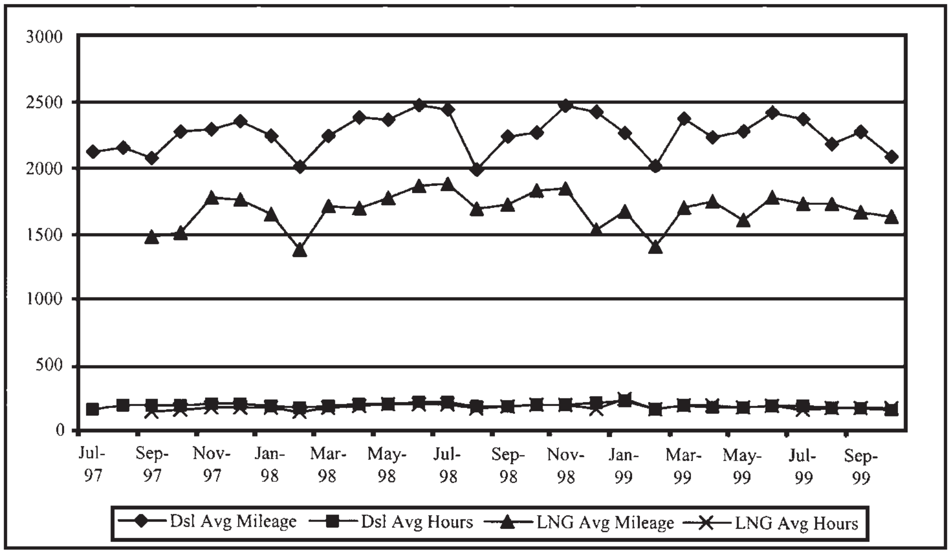


Figure 7. **Fuel economy (mpg) and fuel consumption per engine hour**

Figure 8. Fuel economy per truck based on miles driven

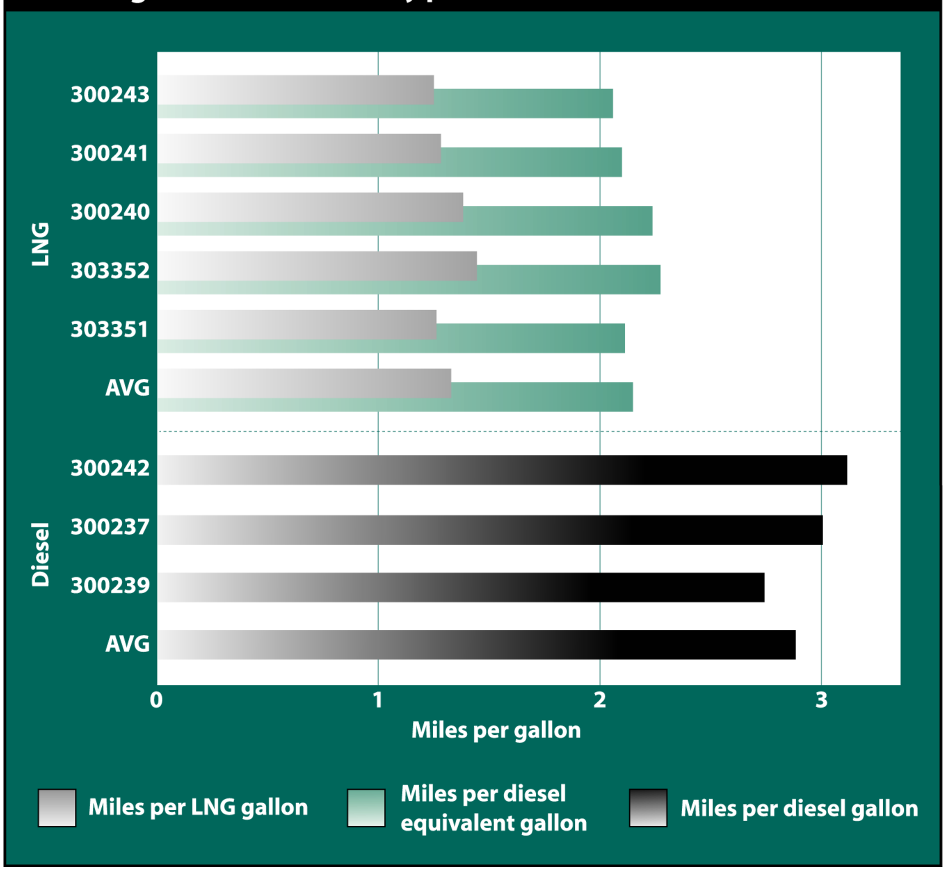


Figure 9. Fuel consumption per truck based on engine hours of operation

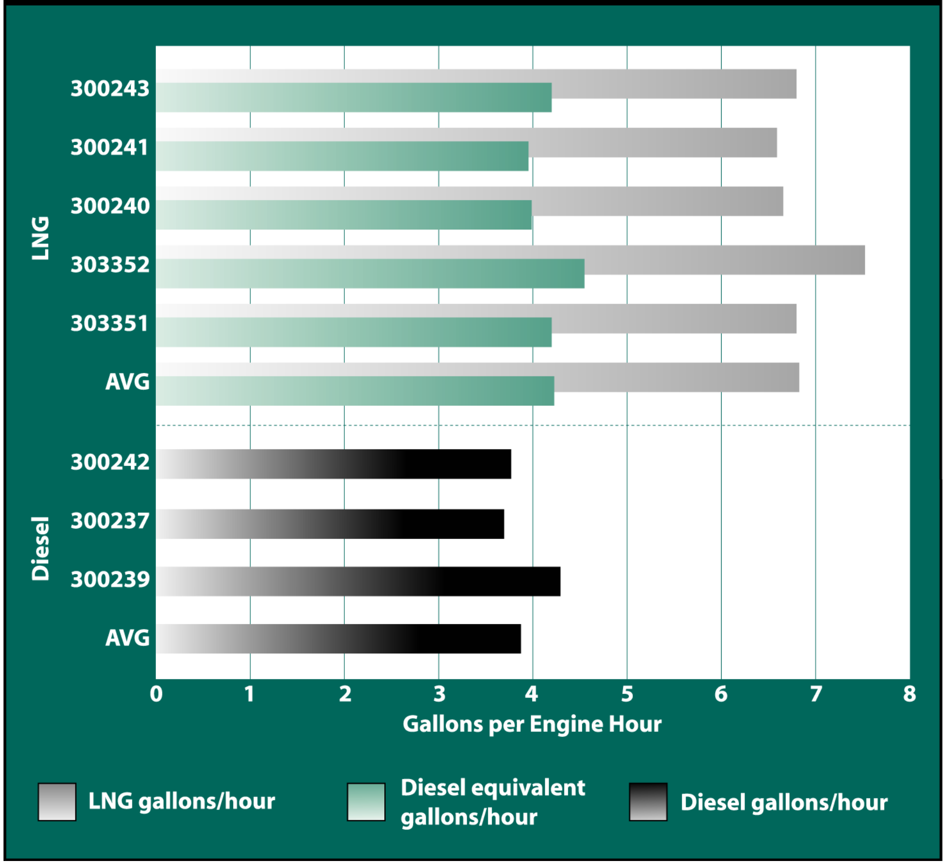


Table 3. Average Fuel Economy and Average Speed

	Truck	mpg/mpeg	Avg Speed mph
Diesel	300242	3.09	11.8
	300237	3.00	11.4
	300239	2.75	11.2
	Diesel Avg	**2.93**	**11.5**
LNG	300243	2.06	8.2
	300241	2.07	8.2
	300240	2.23	8.8
	303352	2.26	10.3
	303351	2.11	8.6
	LNG Avg	**2.14**	**8.7**

As detailed later, the fuel economy was also calculated during the course of emissions testing by West Virginia University (WVU) on controlled duty cycles. Results showed that for the Central Business District (CBD) cycle, the LNG trucks had a fuel economy (miles per gallon/equivalent gallon) that was 9% lower than that of the diesel trucks.

Fuel economy results from the emissions testing were also measured using a duty cycle designed to match the way Waste Management uses its refuse trucks. The diesel equivalent fuel economy results for the Waste Management cycle were 12% lower.

Fuel Cost per Gallon

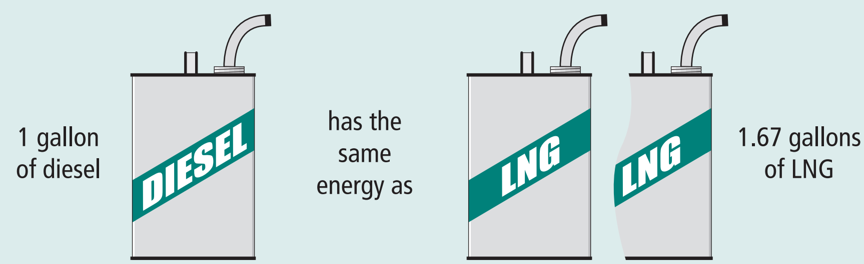
The diesel fuel costs were $1.10 to $1.30 per gallon, including federal and state taxes. An average of $1.20 per gallon for diesel fuel was used for the evaluation.

LNG fuel cost used for the evaluation was $1.059 per LNG gallon or $1.77 per diesel equivalent gallon. Waste Management pays a very high price for LNG in Washington, Pennsylvania, because no transportation-grade LNG is available nearby. The cost to Waste Management (before taxes) is $0.35 per LNG gallon for the fuel plus $0.53 per LNG gallon for transportation costs, totaling $0.88 per LNG gallon. Other LNG sites in the United States have reported costs of $0.45 to $0.50 per LNG gallon.

Small-scale liquefaction, which is being developed at the operations site in Washington, Pennsylvania, should significantly reduce the price paid for LNG.

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.



Fuel Cost per Mile

The average fuel costs ($1.77 per diesel equivalent gallon for LNG trucks; $1.20 per gallon for diesel trucks), coupled with the difference in energy equivalent fuel economies, were used to determine fuel cost per mile for this evaluation.

For the evaluation period, the cost per mile for fuel was $0.410 for diesel and $0.826 for LNG, or 101% higher for LNG. Diesel operation costs were $4.699 per engine hour and LNG operations were $7.233 per engine hour, or 54% higher for LNG.

The LNG fuel cost at Washington, Pennsylvania, was high in comparison to other parts of the country with closer access to LNG. With small-scale liquefaction at Washington, Pennsylvania, the LNG fuel cost could be $0.50 per LNG gallon or lower. Diesel fuel costs may climb higher than recent experience to $1.50 per gallon or higher.

LNG fuel costs at $0.50 per LNG gallon would equate to $0.679 per gallon with taxes or $1.13 per diesel equivalent gallon. Using $1.13 per diesel equivalent gallon for LNG and diesel fuel cost of $1.50 per gallon, the in-service experience at Waste Management on a per-mile fuel cost basis for LNG would be 3% higher than diesel and 21% lower than diesel per engine hour.

Engine Oil Consumption and Cost

Engine oil consumption is measured by recording the volume of engine oil added between oil changes. For most heavy-duty engines, a certain level of engine oil consumption is expected.

The LNG trucks consumed 2.01 quarts of oil per 1,000 miles; the diesel trucks consumed 91% less—1.05 quarts per 1,000 miles. Based on engine hours, the diesel trucks consumed 0.83 quarts per 100 engine hours and the LNG trucks consumed 1.75 quarts per 100 engine hours, which represents 2.1 times higher engine oil consumption for LNG.

The higher engine oil consumption by the LNG trucks is expected, because the LNG engine's spark-ignition cycle allows a lower pressure inside the cylinder (than in a diesel engine). This causes a small amount of the oil to be drawn into the cylinder and burned.

The cost of engine oil for the LNG trucks was $1.35 per quart; the diesel engine oil was $0.65 per quart. The significant difference was due to the low ash requirement and low-volume purchase for the engine oil used in the LNG trucks.

The cost per mile was $0.001 for diesel and $0.003 for LNG. Cost per engine hour was $0.008 for diesel and $0.024 for LNG. Engine oil consumption costs were very small compared to the per-mile and per-hour fuel and maintenance costs.

Factors Affecting Maintenance Costs

The maintenance costs for the LNG fleet were significantly higher than expected because Waste Management agreed to provide the resources for its mechanics to troubleshoot and service the LNG trucks with minimal support from Mack.

This has been extremely successful in keeping the trucks on the road. However, Waste Management has expended significant resources keeping the LNG trucks running. In other circumstances, such labor costs would have been covered under warranty. At other locations, in-house fleet mechanics may do the work, but the manufacturer reimburses the fleet.

In general, Waste Management has performed all maintenance on the LNG trucks for troubleshooting and service. Mack provided an experienced technician when the problems were difficult to diagnose or when significant work needed to be done. Mack also provided many LNG parts at no charge.

Another factor affecting maintenance costs was the difference in preventive maintenance interval between the fleets (300 engine hours for the LNG trucks and 600 engine hours for the diesel trucks). The LNG trucks had scheduled maintenance parts (fuel filters, engine oil, and spark plugs) that were more expensive and changed more often than the diesel trucks.

Mack increased the oil change interval for the LNG trucks to 600 engine hours after the data collection period. Mack is considering increasing the oil change interval for the LNG trucks to 900 engine hours.

Maintenance Costs by Vehicle System

In the comparison between LNG and diesel trucks, maintenance cost differences should be expected only in the engine- and fuel-related systems and the inspection costs. All maintenance costs by vehicle system are provided in this analysis to put the engine- and fuel-related maintenance costs into perspective of the total maintenance cost and the maintenance cost for other vehicle systems. The maintenance costs for the vehicle systems other than the engine- and fuel-related systems and inspections may be significantly higher or lower for the LNG trucks but are not considered to be caused by the natural gas fuel or related vehicle systems.

Figure 10 shows the relative share of the six major truck systems contributing to each fleet's per-mile maintenance costs. Costs calculated per mile did not vary greatly from the costs per engine operating hour by percentage.

Five of the top six systems contributing to maintenance costs are common for diesel and LNG trucks:

1. Tires.

2. Frame, steering, and suspension, including bumper repairs, steering repairs, and suspension repairs such as shock absorbers. This category also includes preventive maintenance for lubricating the suspension and steering systems. The trucks at Waste Management have this action performed once a week while the trucks are in service.

3. PTO and hydraulics, including the power take-off, hydraulic system, and garbage packer body.

4. Brakes.

5. Engine and fuel-related systems, including exhaust, fuel, engine, non-lighting electrical, air intake, and cooling repairs.

The other major contributor to maintenance costs for the diesel fleet was lighting. For the LNG trucks, the other major category was cab, body, and accessories (body repairs, repairs following accidents, glass, and painting; cab and sheet metal repairs, including seats and doors; and accessories such as radios).

Tires were the highest maintenance cost element for both fleets (27% for LNG and 32% for diesel). Engine- and fuel-related systems repairs were the second-highest element (16%) for the LNG trucks but sixth (5%) for the diesel trucks.

Brief summaries of the differences between the diesel and LNG fleets, and some of their causes, are presented here. All results relating to maintenance by vehicle system focus on the similar vehicle lifetimes (12 months).

More detailed maintenance cost results are presented in Appendix A and in the *Final Data Report*.

- Engine- and fuel-related systems – The LNG trucks had much higher costs for these systems (5 times higher based on mileage, nearly 4 times higher based on engine hours). This was caused by more frequent preventive maintenance and higher costs for troubleshooting engine and fuel system issues.

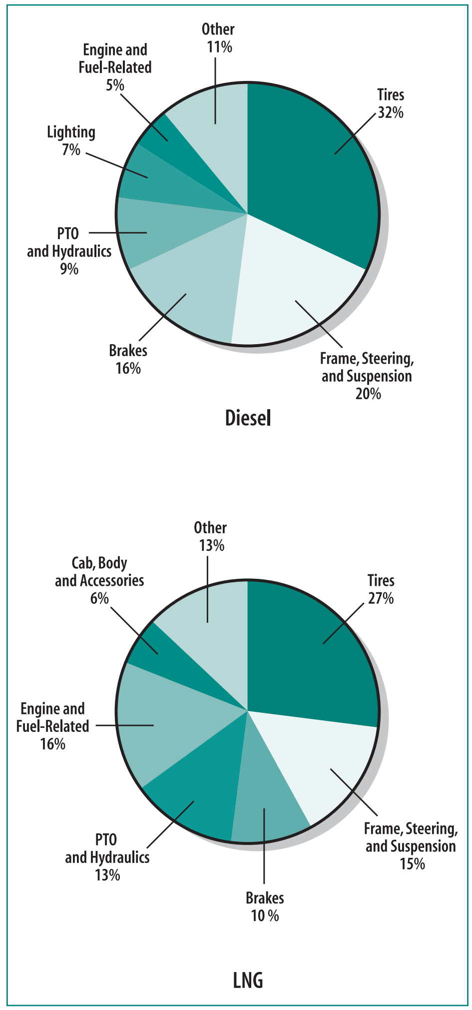
  - Exhaust system – Costs were low for both fleets.

  - Fuel system – The per-mile LNG truck maintenance costs were 6.2 times higher than the diesel trucks; the per-engine hour costs were 4.7 times higher. This was caused by significantly higher labor costs to troubleshoot and repair small LNG leaks and problems with the LNG tanks. Also, the LNG fuel filters cost nearly 10 times more than the diesel fuel filters. The diesel and LNG trucks had some maintenance work for accelerator pedal problems.

  - Engine system – The LNG truck maintenance costs were 6 times higher per mile than the diesel trucks and 4.5 times higher per engine hour. The parts costs for both groups were almost entirely engine oil and filters changed as part of preventive maintenance.

  - Non-lighting electrical systems – The maintenance costs were low for the diesel trucks, only 3 labor hours. The LNG maintenance costs consisted of charging and cranking system problems with one voltmeter and one alternater being replaced.

Figure 10. Share of maintenance costs across major systems



- Air intake system – Costs were low for both fleets.
- Cooling system – Costs were low for both fleets.

• PMA inspections (labor hours only) – The LNG trucks had 70% higher costs for inspections based on mileage and 30% more based on engine hours. The diesel trucks had preventive maintenance every 600 engine hours (3 to 4 times per year), and the LNG trucks had preventive maintenance every 300 engine hours (7 to 8 times per year).

• Cab, body, and accessories systems – The LNG trucks had nearly double the costs for these systems (2.1 times based on mileage and 1.6 times based on engine hours). Maintenance costs for both sets of trucks were for doors, windshields and windows, horns, mirrors, wipers, and mud flaps. There were only a few hours for each truck group to repair minor accident damage.

• Frame, steering, and suspension system – Costs were nearly the same for both fleets.

• PTO and hydraulic systems – The LNG trucks had costs 2.3 times higher based on mileage and 1.7 times higher based on engine hours.

• Axles, wheels, and drive shaft systems – Costs were low for both fleets.

• Tire systems – Costs were nearly the same: the diesel trucks had 38% higher costs based on mileage and only 4% higher based on engine hours.

• Lighting system – Costs were nearly the same. The LNG trucks had 13% higher costs based on mileage and 15% lower costs based on engine hours.

Warranty Costs

Warranty information collected for this project included only work on the engine and fuel systems for the LNG trucks. No warranty information was collected for the diesel trucks, so no warranty cost comparison between the fleets is possible.

As discussed earlier, Waste Management included in its maintenance cost totals a substantial amount of labor cost that normally would have been borne by the truck manufacturer.

Further details on warranty repairs, modifications, and start-up activities were presented in Waste Management's *LNG Truck Fleet: Start-Up Experience.*

Overall Maintenance Costs

Figures 11 and 12 show the total maintenance costs by fleet based on mileage and engine hours, respectively. The figures also show miles or hours per truck, and breakouts for the separate parts and labor elements of the total maintenance costs.

For this analysis, labor costs were held constant at $50 per hour. The focus of the analysis was on similar vehicle lifetimes (12 months).

Overall, the maintenance costs per mile (Figure 11) were 63% higher for the LNG trucks. The average vehicle mileage was 31% lower, the parts costs were nearly the same (1% lower), and the labor hours were 20% higher for the LNG trucks.

Figure 12 shows that the maintenance costs per engine hour were 23% higher for the LNG trucks. The LNG and diesel vehicles had comparable usage as measured by engine hours, 9% lower for the LNG trucks. A similar usage basis for the maintenance costs shows a more accurate comparison of costs.

The higher labor hours were caused by a higher rate of repairs for the hydraulic system/packer body and troubleshooting labor for the engine and fuel systems for the LNG trucks. These costs should decrease over time with more mechanic experience.

Overall Operating Costs

Figure 13 provides a summary of operating costs (without driver labor) based on vehicle mileage. Figure 14 provides a similar summary based on vehicle engine hours of operation. These results are for similar vehicle lifetime data periods.

Overall, the LNG trucks had significantly higher costs than the diesel trucks, 80% higher based on mileage and 37% higher based on engine hours. As mentioned earlier, Waste Management's LNG was very expensive at $0.88 per LNG gallon (before taxes), and Waste Management incurred substantial unreimbursed expenses for maintenance on the trucks under warranty, unlike prevailing industry practice for new vehicles.

Future operating costs should decrease with the addition of small-scale liquefaction at the Washington, Pennsylvania, site. With more experience with the LNG trucks, troubleshooting labor costs should also decline.

Figure 11. Total maintenance cost per truck, based on mileage

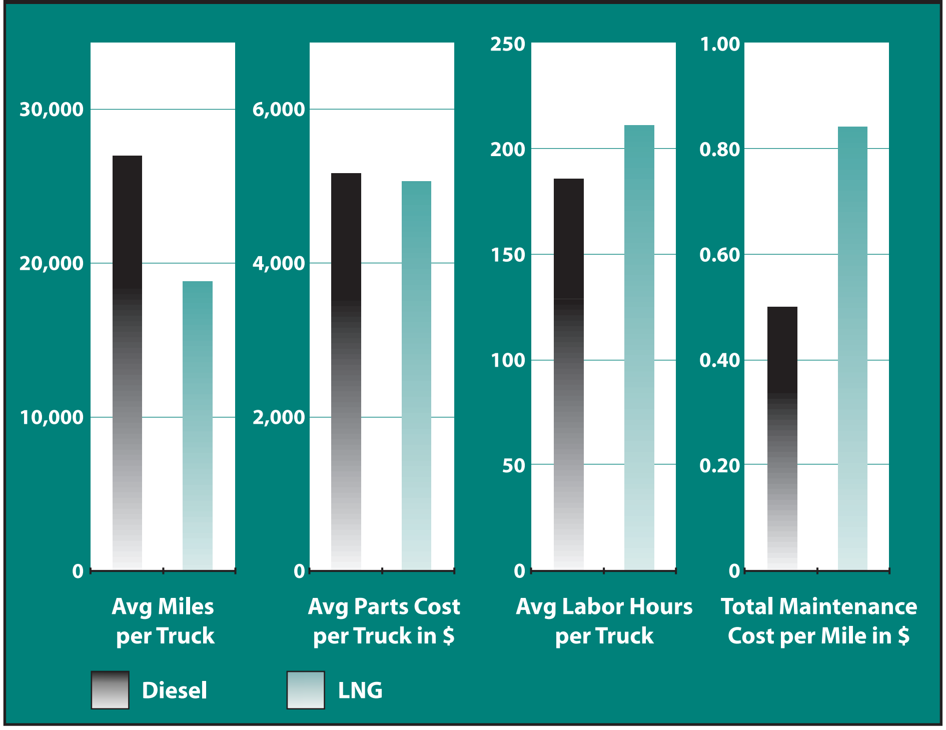


Figure 12. Total maintenance cost per truck, based on hours

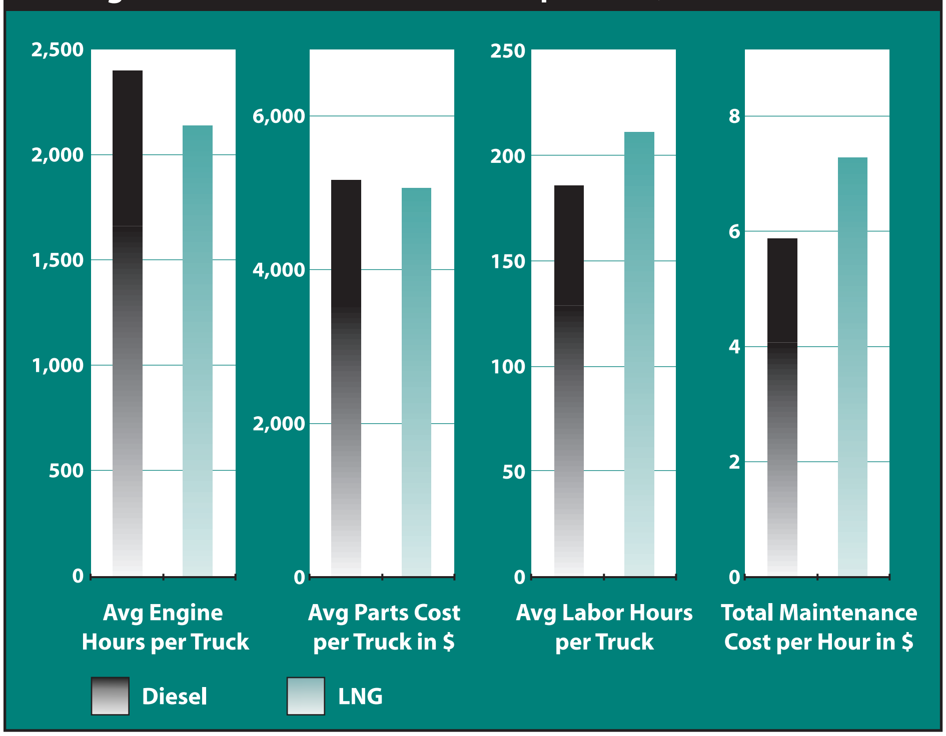


Figure 13. Overall operating costs, based on mileage

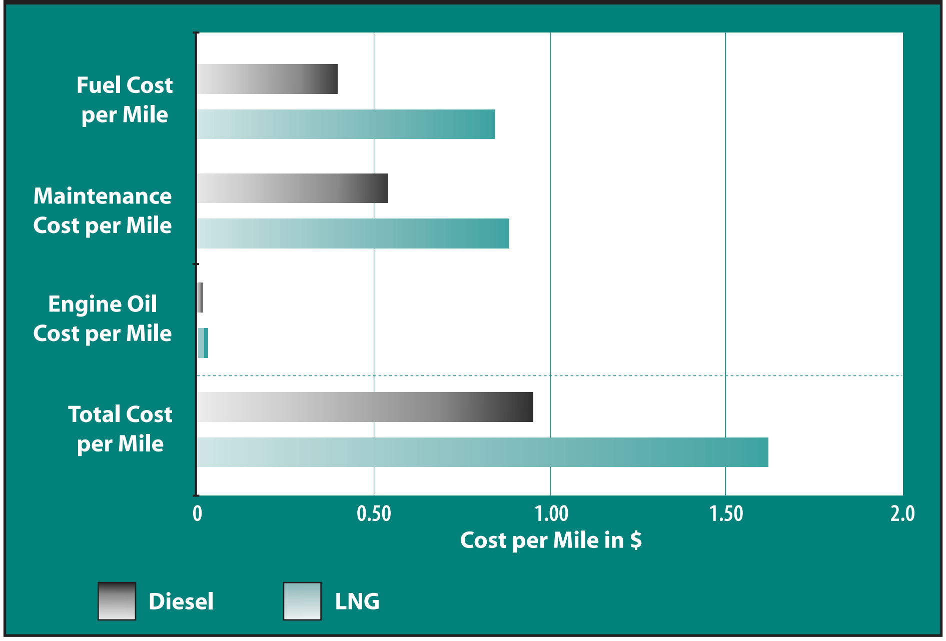
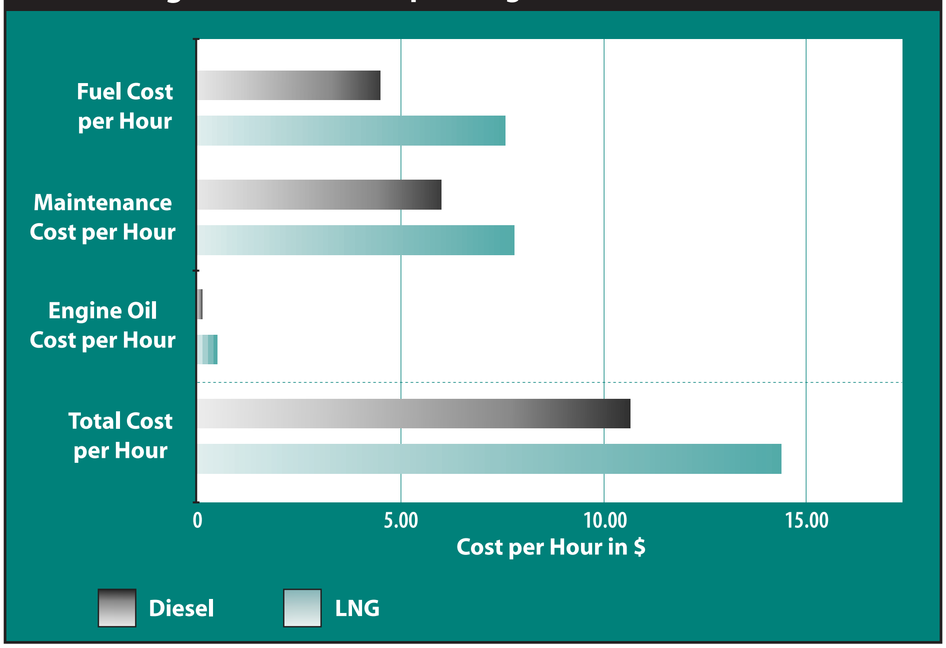


Figure 14. Overall operating costs, based on hours



Similar preventive maintenance periods will also show a significant reduction in maintenance costs for the LNG trucks.

Emissions Testing Results

Emissions tests on the diesel trucks and six LNG trucks were conducted by the WVU Department of Mechanical and Aerospace Engineering using one of its transportable heavy-duty chassis dynamometer emissions laboratories (developed under DOE sponsorship).

WVU used the standard CBD speed-versus-time cycle to evaluate each truck. WVU also measured the operation of trucks in service, then developed a customized test cycle that represents the operation of the trucks more closely than the CBD cycle. The average speed for the CBD cycle is 12.7 mph, for the Waste Management cycle, 10.6 mph.

WVU evaluated emissions from Waste Management's trucks in January and February 2000. Detailed emissions testing results are presented in Appendix B and in the *Final Data Report*.

Figure 15 shows the emissions testing results for the CBD duty cycle, and Figure 16 shows the emissions testing results for the Waste Management duty cycle.

Turbocharger Effects on NO_x Emissions

The emissions testing revealed that three LNG trucks were emitting high nitrogen oxide (NO_x) levels compared to the diesel and the other LNG trucks. The problem was traced to faulty turbochargers, which Mack has since resolved by changing suppliers.

Figure 15. Emissions testing results, CBD cycle

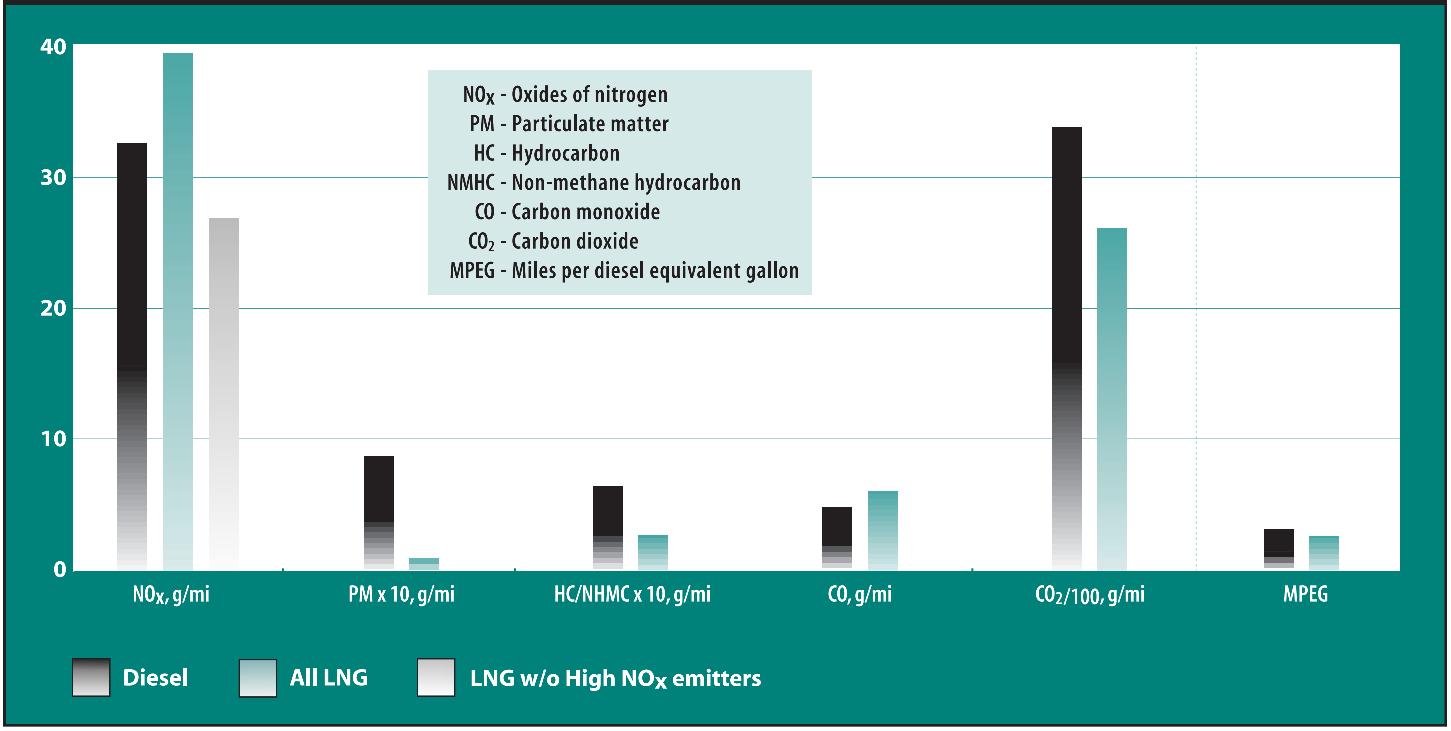
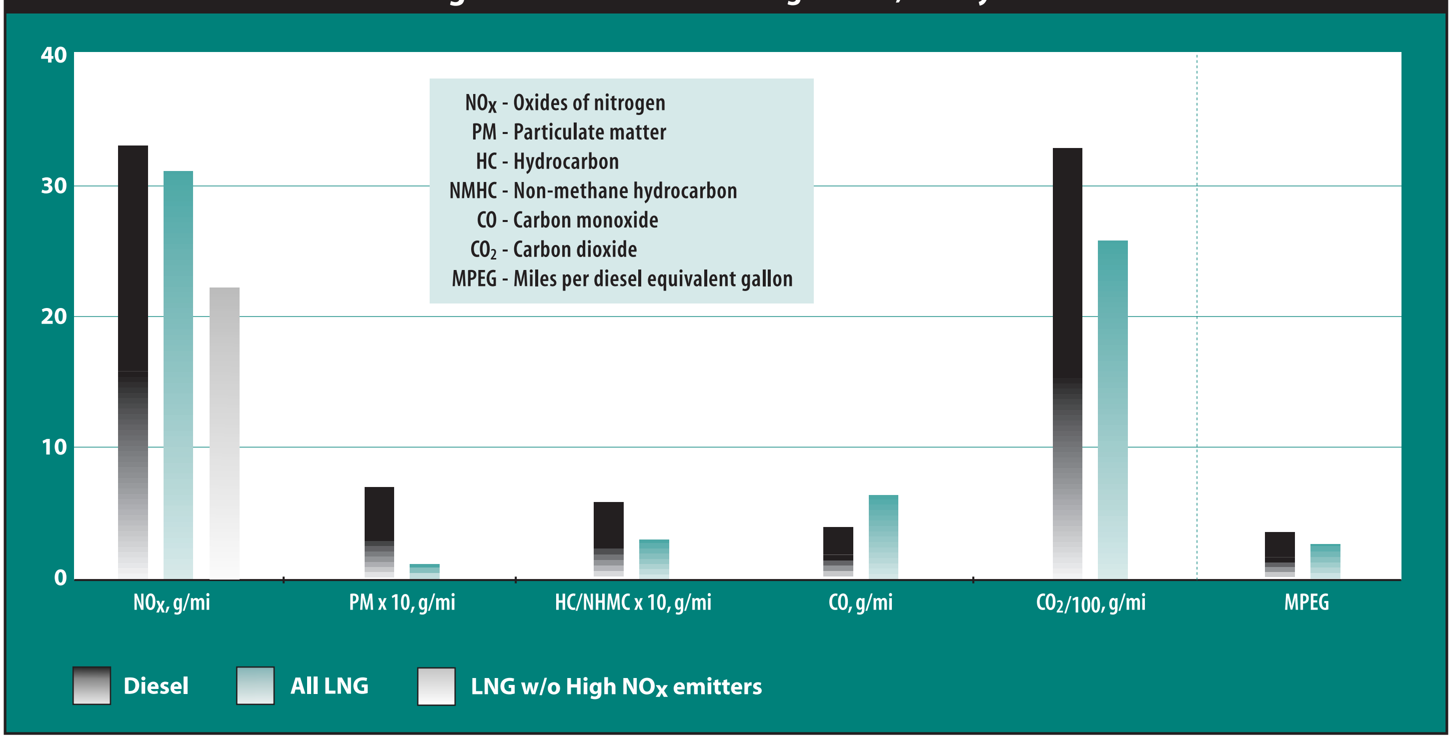


Figure 16. Emissions testing results, WM cycle



Because this problem appears to be a specific equipment problem related only to NO_x emissions, the NO_x results are shown for all LNG trucks and then without the high NO_x LNG trucks. Unless otherwise noted, references to LNG trucks include all the LNG trucks tested by WVU.

CBD Duty Cycle Results

On the CBD cycle (Figure 15), the LNG trucks had 40% higher carbon monoxide (CO) and 94% lower particulate matter (PM). The LNG trucks, on average, had 22% higher NO_x with the high emitters included. Excluding the three high NO_x emitters from the comparison, the LNG trucks had a result 16% lower.

When comparing non-methane hydrocarbons (NMHC) for the LNG trucks and hydrocarbons (HC) for the diesel control trucks (all HC emissions for the diesel trucks are assumed to be non-methane), the results showed that the LNG trucks had significantly lower emissions.

The LNG trucks also had 21% lower levels of carbon dioxide (CO_2). The average miles per diesel equivalent gallon (mpeg) for the LNG trucks obtained during emissions testing was much higher than the result obtained from in-use fuel economy data, as discussed earlier. The LNG truck mpeg was only 9% lower than the mpg measured for diesel trucks on the CBD cycle.

Waste Management Duty Cycle Results

On the Waste Management cycle (Figure 16), the LNG trucks had 80% higher CO and 86% lower PM. The LNG trucks, on average, had 4% lower NO_x with the high emitters included. Excluding the high NO_x emitters from the comparison, the LNG trucks had a result 32% lower.

When comparing NMHC for the LNG trucks and HC for the diesel control trucks, the results showed that the LNG trucks had significantly lower emissions. The LNG trucks also had 18% lower levels of CO_2. The LNG truck mpeg was only 12% lower than the mpg measured for the diesel trucks on the Waste Management cycle.

U.S. EPA Emissions Certification

The U.S. Environmental Protection Agency (EPA) certification standard for engines from model years 1998 through 2001, along with the emissions certification testing data from Mack diesel and natural gas engines for model year 2000. The Mack engines meet the standards for all emission species. (See Table 4.)

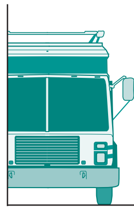
The certification test is performed on an engine in a laboratory. The results are expressed in grams per brake-horsepower hour, and thus differ from the values shown in Figures 15 and 16 from the WVU emissions testing. Because the EPA certification tests are engine based rather than vehicle based and use a different testing cycle, there is no direct comparison between the EPA values and the chassis dynamometer emissions testing results from WVU.

Table 4. **Engine Certification Level and Data (grams per brake-horsepower hour)**

Standard/ Certification	Non-Methane (Total) Hydrocarbons	Carbon Monoxide	Oxides of Nitrogen	Particulate Matter
	NMHC (HC)	CO	NO_x	PM
1998+ Truck	1.2 (1.3)	15.5	4.0	0.10
Mack EM7-300 Diesel	0.11	Waiver*	3.669**	0.081
Mack E7G-350 NG	0.276	1.32	2.323**	0.026

* Mack waived the CO measurement based on diesel engines historically having low CO emissions.

** The results for NO_x include a deterioration factor developed for each engine family.



Summary and Conclusions

Based on the evaluation of the Waste Management LNG trucks used in Washington, Pennsylvania, we can conclude several major points:

- In general, the LNG trucks were used in a similar manner as the diesel trucks, and the LNG trucks met all requirements for operation. The monthly average mileage (miles driven) per truck was 26% lower for the LNG trucks, but the monthly average engine hours per truck were only 3% lower for the LNG trucks.
- The LNG trucks were used to haul 34% more refuse by weight each day. Another difference in operation was a lower average speed (8.7 mph for LNG and 11.5 mph for diesel).
- Drivers and refuse workers report no difference in power between the LNG and diesel trucks. The refuse workers prefer the LNG trucks because of the lack of diesel exhaust smell, which is important to them because they have to walk behind the trucks. Also, they prefer the quieter operation of the LNG trucks.
- Emissions testing results from testing on a portable chassis dynamometer using two duty cycles showed much lower PM emissions for the LNG trucks. The NMHC emissions for the LNG trucks were much lower than the HC emissions for the diesel trucks. CO_2 emissions were 18% to 21% lower for the LNG trucks, and CO emissions were 40% to 80% higher for the LNG trucks.
- Results for NO_x emissions are more difficult to interpret. Three of the LNG trucks tested had higher than expected NO_x emissions, traced by Mack to a malfunctioning turbocharger (Mack has changed suppliers for new engines). When those trucks are not included in the analysis, the LNG trucks had 16% lower NO_x than the diesel trucks on the CBD cycle and 32% lower NO_x than the diesel trucks on the Waste Management cycle.
- Diesel equivalent per-mile fuel economy was 27% lower for the LNG trucks for in-use operation. Diesel equivalent fuel consumption per engine hour was only 4% higher for the LNG trucks.

  The in-service fuel economy was affected by the lower average operating speed of the LNG trucks compared to the diesel trucks and the LNG trucks being used to haul more refuse (by weight) than the diesel trucks each day.
- Per-mile fuel economy measured during the emissions testing showed that the LNG trucks had diesel equivalent gallon fuel economy 9% lower for the CBD cycle and 12% lower for the Waste

Management cycle. Because the trucks were operated with the same packer load and over the same driving cycle during the emissions tests, the comparison more clearly indicates the effect of the fuel on fuel economy than the in-use comparison.

- Per-mile maintenance costs for the LNG trucks were 63% higher and engine-hour costs 23% higher. For the engine- and fuel-related systems (the engine, fuel, air intake, cooling, and non-lighting electrical systems), the per-mile maintenance costs were 5.1 times higher for the LNG trucks and per-engine-hour costs 3.8 times higher.
- Waste Management in Washington, Pennsylvania, has been dedicated to operating the LNG trucks, and agreed to do most of the warranty work without reimbursement from Mack. The mechanics have learned to troubleshoot and service the LNG trucks with much less support from the manufacturer compared to other alternative fuel operations or other new technology development projects.

  This has caused the maintenance costs to be significantly higher than expected for the LNG trucks, and these costs are expected to decrease significantly with more experience in operation. Mack has been extremely responsive to Waste Management's needs to make changes to the LNG trucks, and provides parts on short notice.

  Also, these high costs were affected by the preventive maintenance schedule being twice as often for the LNG trucks. Mack has since made the preventive maintenance cycle the same as for diesel (in model year 2000), 600 engine hours. Mack is considering increasing the maintenance interval for the LNG trucks by 50% to 900 engine hours.
- During the data collection and evaluation, Waste Management paid $0.88 per LNG gallon (before taxes), an extremely high price compared to other alternative fuel sites. Other LNG sites in the United States have reported costs of $0.45 to $0.50 per LNG gallon.

  Transportation-grade LNG has to be trucked in from the western United States at a significant cost. Options for small-scale liquefaction are being explored on-site using natural gas from the Columbia Gas pipeline. Landfill gas may be used in the future.
- Overall, the LNG trucks cost 80% more to operate per mile and 37% more per engine hour. Total operating costs excluded driver labor, but included fuel and engine oil consumption costs and maintenance costs.
- The LNG fuel station was installed with the storage tank underground. It is reportedly operating well, although problems were reported with the fuel nozzle (leaking and difficulty getting on and off the truck fuel tank). There was a problem with the dispenser readout, but there have been no major operations problems.

Future LNG Operations at Waste Management

Currently, Waste Management in Washington, Pennsylvania, has seven LNG trucks in service. There are no plans to purchase more LNG trucks. The main issue is the cost of LNG fuel.

Alternative fuel project partners affiliated with the site, led by Chart Industries, Inc., and Brookhaven National Laboratory, are developing an on-site small-scale liquefaction capability. It will use natural gas from the Columbia Gas pipeline. Landfill gas may also be used in the future as the feedstock. Having on-site fuel production is expected to bring the fuel cost down to the $0.50 per LNG gallon range.

Waste Management is commited to cleaner burning truck technologies. During the next two years, Waste Management plans to deploy approximately 200 LNG refuse collection trucks in locations throughout California.

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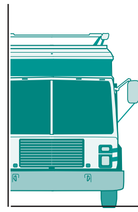

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Appendix A

Fleet Summary Statistics

Appendix A Fleet Summary Statistics

Table A-1. Waste Management of PA (Washington, PA)
Fleet Summary Statistic (Based on Engine Hours and Mileage)
Fleet Operations and Economics **Similar Vehicle Lifetimes**

	Diesel Control	LNG
Number of Vehicles	3	5
Period Used for Fuel and Oil Op Analysis	11/98 - 10/99	11/98 - 10/99
Total Number of Months in Period	12	12
Fuel and Oil Analysis Base Engine Hours	6,678	7,895
Period Used for Maintenance Op Analysis	12 Month	12 Month
Total Number of Months in Period	12	12
Maintenance Analysis Base Engine Hours	7,230	10,979
Average Monthly Engine Hours per Vehicle	200	195
Average Speed	11.47	8.67
Fleet Fuel Usage in Diesel #2 Equiv. Gal.	26,149	32,291
LNG Gallons per Hour (GPH)		6.81
Representative Fleet GPH (energy equiv)	3.92	4.09
Ratio of GPH (AF/DC)		1.04
Average Fuel Cost as Reported (with tax)	1.20	1.06
	per Gal D2	per Gal LNG
Average Fuel Cost per Energy Equivalent	1.20	1.77
Fuel Cost per Hour	4.699	7.233
Number of Make-Up Oil Quarts per Hour	0.012	0.017
Oil Cost per Quart	0.65	1.35
Oil Cost per Hour	0.008	0.024
Total Scheduled Repair Cost per Hour	1.394	1.673
Total Unscheduled Repair Cost per Hour	4.559	5.646
Total Maintenance Cost per Hour	5.954	7.319
Total Operating Cost per Hour	**10.660**	**14.576**

Fleet Operations and Economics **Similar Vehicle Lifetimes**

	Diesel Control	LNG
Number of Vehicles	3	5
Period Used for Fuel and Oil Op Analysis	11/98 - 10/99	11/98 - 10/99
Total Number of Months in Period	12	12
Fuel and Oil Analysis Base Fleet Mileage	76,514	69,106
Period Used for Maintenance Op Analysis	12 Month	12 Month
Total Number of Months in Period	12	12
Maintenance Analysis Base Fleet Mileage	82,866	95,143
Average Monthly Mileage per Vehicle	2,295	1,688
Average Speed (mph)	11.47	8.67
Fleet Fuel Usage in Diesel #2 Equiv. Gal.	26,149	32,291
LNG MPG		1.28
Representative Fleet MPG (energy equiv)	2.93	2.14
Ratio of MPG (AF/DC)		0.73
Average Fuel Cost as Reported (with tax)	1.20	1.06
	per Gal D2	per Gal LNG
Average Fuel Cost per Energy Equivalent	1.20	1.77
Fuel Cost per Mile	0.410	0.826
Number of Make-Up Oil Quarts per Mile	0.001	0.002
Oil Cost per Quart	0.65	1.35
Oil Cost per Mile	0.001	0.003
Total Scheduled Repair Cost per Mile	0.122	0.193
Total Unscheduled Repair Cost per Mile	0.398	0.651
Total Maintenance Cost per Mile	0.519	0.845
Total Operating Cost per Mile	**0.930**	**1.674**

Maintenance Costs

	Diesel Control	LNG
Fleet Engine Hours	7,230	10,979
Fleet Mileage	82,866	95,143
Total Parts Cost	15,544.01	25,536.04
Total Labor Hours	550.0	1096.3
Average Labor Cost	27,500.00	54,815.00
(@ $50.00 per hour)		
Total Maintenance Cost	43,044.01	80,351.04
Monthly Maintenance Cost per Truck	1,195.67	1,691.60
Total Maintenance Cost per Hour	**5.954**	**7.319**
Total Maintenance Cost per Mile	**0.519**	**0.845**

Breakdown of Maintenance Costs by Vehicle System

	Diesel Control	LNG
Fleet Engine Hours	7,230	10,979
Fleet Mileage	82,866	95,143
Total Engine/Fuel-Related Systems (ATA VMRS 30, 31, 32, 33, 41, 42, 43, 44, 45)		
Parts Cost	725.52	3,671.81
Labor Hours	29.3	180.9
Average Labor Cost	1,462.50	9,045.00
Total Cost (for system)	2,188.02	12,716.81
Monthly Cost (for system) per Truck	60.78	267.72
Total Cost (for system) per Hour	**0.3026**	**1.1583**
Total Cost (for system) per Mile	**0.0264**	**0.1337**
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost	97.61	21.91
Labor Hours	1.8	7.6
Average Labor Cost	87.50	380.00
Total Cost (for system)	185.11	401.91
Monthly Cost (for system) per Truck	5.14	8.46
Total Cost (for system) per Hour	**0.0256**	**0.0366**
Total Cost (for system) per Mile	**0.0022**	**0.0042**
Fuel System Repairs (ATA VMRS 44)		
Parts Cost	52.08	1,040.76
Labor Hours	11.0	65.7
Average Labor Cost	550.00	3,285.00
Total Cost (for system)	602.08	4,325.76
Monthly Cost (for system) per Truck	16.72	91.07
Total Cost (for system) per Hour	**0.0833**	**0.3940**
Total Cost (for system) per Mile	**0.0073**	**0.0455**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Control	LNG
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost	437.38	1,744.74
Labor Hours	8.0	80.3
Average Labor Cost	400.00	4,012.50
Total Cost (for system)	837.38	5,757.24
Monthly Cost (for system) per Truck	23.26	121.21
Total Cost (for system) per Hour	**0.1158**	**0.5244**
Total Cost (for system) per Mile	**0.0101**	**0.0605**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts Cost	0.00	656.07
Labor Hours	3.0	19.8
Average Labor Cost	150.00	987.50
Total Cost (for system)	150.00	1,643.57
Monthly Cost (for system) per Truck	4.17	34.60
Total Cost (for system) per Hour	**0.0207**	**0.1497**
Total Cost (for system) per Mile	**0.0018**	**0.0173**
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost	76.28	130.73
Labor Hours	3.0	1.0
Average Labor Cost	150.00	50.00
Total Cost (for system)	226.28	180.73
Monthly Cost (for system) per Truck	6.29	3.80
Total Cost (for system) per Hour	**0.0313**	**0.0165**
Total Cost (for system) per Mile	**0.0027**	**0.0019**
Cooling System Repairs (ATA VMRS 42)		
Parts Cost	62.17	77.60
Labor Hours	2.5	6.6
Average Labor Cost	125.00	330.00
Total Cost (for system)	187.17	407.60
Monthly Cost (for system) per Truck	5.20	8.58
Total Cost (for system) per Hour	**0.0259**	**0.0371**
Total Cost (for system) per Mile	**0.0023**	**0.0043**
Brake System Repairs (ATA VMRS 13)		
Parts Cost	1,986.00	2,205.84
Labor Hours	94.0	123.9
Average Labor Cost	4,700.00	6,192.50
Total Cost (for system)	6,686.00	8,398.34
Monthly Cost (for system) per Truck	185.72	176.81
Total Cost (for system) per Hour	**0.9248**	**0.7649**
Total Cost (for system) per Mile	**0.0807**	**0.0883**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Control	LNG
Transmission Repairs (ATA VMRS 27)		
Parts Cost	275.28	547.54
Labor Hours	4.5	11.6
Average Labor Cost	225.00	580.00
Total Cost (for system)	500.28	1,127.54
Monthly Cost (for system) per Truck	13.90	23.74
Total Cost (for system) per Hour	**0.0692**	**0.1027**
Total Cost (for system) per Mile	**0.0060**	**0.0119**
PTO and Hydraulic Repairs (ATA VMRS 56-PTO, 65-Hydraulic)		
Parts Cost	634.13	1,140.16
Labor Hours	65.5	179.3
Average Labor Cost	3,275.00	8,962.50
Total Cost (for system)	3,909.13	10,102.66
Monthly Cost (for system) per Truck	108.59	212.69
Total Cost (for system) per Hour	**0.5407**	**0.9202**
Total Cost (for system) per Mile	**0.0472**	**0.1062**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost	484.59	929.17
Labor Hours	28.5	71.9
Average Labor Cost	1,425.00	3,592.50
Total Cost (for system)	1,909.59	4,521.67
Monthly Cost (for system) per Truck	53.04	95.19
Total Cost (for system) per Hour	**0.2641**	**0.4118**
Total Cost (for system) per Mile	**0.0230**	**0.0475**
Inspections Only - no parts replacements (101)		
Parts Cost	0.00	0.00
Labor Hours	42.3	83.0
Average Labor Cost	2,112.50	4,150.00
Total Cost (for system)	2,112.50	4,150.00
Monthly Cost (for system) per Truck	58.68	87.37
Total Cost (for system) per Hour	**0.2922**	**0.3780**
Total Cost (for system)per Mile	**0.0255**	**0.0436**
HVAC System Repairs (ATA VMRS 01)		
Parts Cost	0.00	18.87
Labor Hours	2.0	3.4
Average Labor Cost	100.00	170.00
Total Cost (for system)	100.00	188.87
Monthly Cost (for system) per Truck	2.78	3.98
Total Cost (for system) per Hour	**0.0138**	**0.0172**
Total Cost (for system) per Mile	**0.0012**	**0.0020**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Control	LNG
Air System Repairs (ATA VMRS 10)		
Parts Cost	5.65	27.42
Labor Hours	5.5	8.5
Average Labor Cost	275.00	425.00
Total Cost (for system)	280.65	452.42
Monthly Cost (for system) per Truck	7.80	9.52
Total Cost (for system) per Hour	**0.0388**	**0.0412**
Total Cost (for system) per Mile	**0.0034**	**0.0048**
Lighting System Repairs (ATA VMRS 34)		
Parts Cost	306.85	354.51
Labor Hours	53.5	70.3
Average Labor Cost	2,675.00	3,512.50
Total Cost (for system)	2,981.85	3,867.01
Monthly Cost (for system) per Truck	82.83	81.41
Total Cost (for system) per Hour	**0.4124**	**0.3522**
Total Cost (for system) per Mile	**0.0360**	**0.0406**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts Cost	788.92	395.26
Labor Hours	151.3	232.5
Average Labor Cost	7,562.50	11,622.50
Total Cost (for system)	8,351.42	12,017.76
Monthly Cost (for system) per Truck	231.98	253.01
Total Cost (for system) per Hour	**1.1551**	**1.0946**
Total Cost (for system) per Mile	**0.1008**	**0.1263**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 12-Tag Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost	24.34	224.37
Labor Hours	5.3	17.8
Average Labor Cost	262.50	887.50
Total Cost (for system)	286.84	1,111.87
Monthly Cost (for system) per Truck	7.97	23.41
Total Cost (for system) per Hour	**0.0397**	**0.1013**
Total Cost (for system) per Mile	**0.0035**	**0.0117**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Control	LNG
Tire Repairs (ATA VMRS 17)		
Parts Cost	10,312.73	16,021.09
Labor Hours	68.5	113.5
Average Labor Cost	3,425.00	5,675.00
Total Cost (for system)	13,737.73	21,696.09
Monthly Cost (for system) per Truck	381.60	456.76
Total Cost (for system) per Hour	**1.9001**	**1.9761**
Total Cost (for system) per Mile	**0.1658**	**0.2280**

Appendix B

Emissions Test Results

Appendix B Emissions Test Results

Table B-1. Emissions Testing at Waste Management in Washington, Pennsylvania

Results from CBD Cycle Emissions Testing (g/mi)

Test ID	WVU Ref Num	Fuel	Model Yr	Odometer	Cycle	CO	NO_x	HC	PM	CO_2	MPG	Btu	CH_4	NMHC
3562	WHM-300237-D2-3CBD	D2	1997	71600	3CBD	5.2	32.5	0.70	0.99	3400	2.98	43568		
3598	WHM-300239-D2-3CBD	D2	1997	69500	3CBD	4.6	32.6	0.62	0.88	3398	2.99	43529		
					Average	**4.9**	**32.6**	**0.66**	**0.93**	**3399**	**2.99**	**43548**		
3569	WHM-300240-LNG-3CBD	LNG	1998	33900	3CBD	6.6	50.6	18.6	0.07	2700	2.72	47212	16.3	0.24
3572	WHM-300241-LNG-3CBD	LNG	1998	41000	3CBD	6.7	54.0	15.9	0.07	2720	2.71	47426	15.4	0.19
3575,3577	WHM-300243-LNG-3CBD	LNG	1997	45400	3CBD	6.4	22.8	16.8	0.05	2554	2.88	44628	15.0	0.12
3580	WHM-300489-LNG-3CBD	LNG	1999	12800	3CBD	6.6	28.3	29.4	0.02	2749	2.65	48563	26.7	0.22
3567	WHM-303351-LNG-3CBD	LNG	1999	15000	3CBD	7.5	51.6	16.8	0.07	2748	2.68	47967	15.2	0.20
3583	WHM-303352-LNG-3CBD	LNG	1999	17100	3CBD	7.3	31.1	23.7	0.07	2706	2.70	47569	21.4	0.28
			Average:			**6.9**	**39.7**	**20.2**	**0.06**	**2696**	**2.72**	**47228**	**18.3**	**0.21**
			Percent Difference:			**40.4**	**22.0**		**-93.7**	**-20.7**	**-8.8**	**8.4**		**-68.6**
			Average, High NO_x Removed:				**27.4**							
			Percent Difference:				**-15.9**							

Results from Waste Management Cycle Emissions Testing (g/mi)

Test ID	WVU Ref Num	Fuel	Model Yr	Odometer	Cycle	CO	NO_x	HC	PM	CO_2	MPG	Btu	CH_4	NMHC
3563	WHM-300237-D2-WHM	D2	1997	71600	WHM	4.2	32.7	0.66	0.77	3230	3.14	41377		
3599	WHM-300239-D2-WHM	D2	1997	69500	WHM	3.7	33.2	0.63	0.71	3340	3.04	42774		
					Average:	**3.9**	**33.0**	**0.64**	**0.74**	**3285**	**3.09**	**42075**		
3570	WHM-300240-LNG-WHM	LNG	1998	33900	WHM	6.7	38.5	20.2	0.06	2718	2.70	47604	18.3	0.27
3573	WHM-300241-LNG-WHM	LNG	1998	41000	WHM	6.9	46.6	18.8	0.10	2702	2.72	47271	16.9	0.25
3578	WHM-300243-LNG-WHM	LNG	1997	45400	WHM	6.8	19.5	20.5	0.11	2658	2.76	46582	18.5	0.27
3581	WHM-300489-LNG-WHM	LNG	1999	12800	WHM	7.0	23.2	33.2	0.05	2587	2.80	45977	30.1	0.21
3566	WHM-303351-LNG-WHM	LNG	1999	15000	WHM	7.4	38.4	16.2	0.23	2751	2.68	47998	14.6	0.24
3584	WHM-303352-LNG-WHM	LNG	1999	17100	WHM	7.3	24.1	27.2	0.08	2707	2.69	47751	24.6	0.31
			Average:			**7.0**	**31.7**	**22.7**	**0.10**	**2687**	**2.72**	**47197**	**20.5**	**0.26**
			Percent Difference:			**79.5**	**-3.8**		**-85.9**	**-18.2**	**-11.9**	**12.2**		**-59.6**
			Average, High NO_x Removed:				**22.3**							
			Percent Difference:				**-32.4**							

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