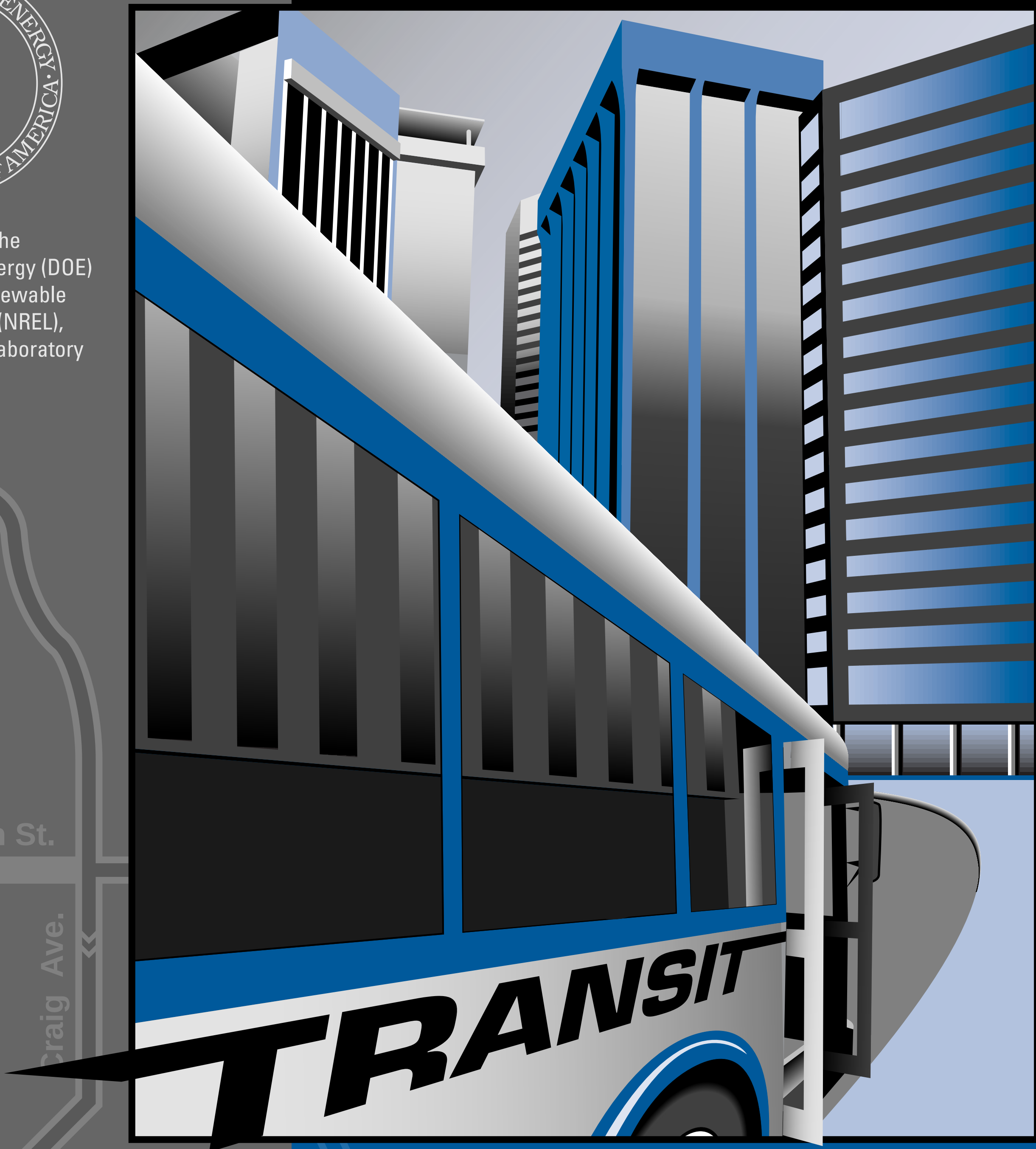
Alternative Fuel Transit Buses



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DART's LNG Bus Fleet

Final Results

DALLAS AREA RAPID TRANSIT'S (DART) LNG BUS FLEET: Final Results

Alternative Fuel Transit Bus Evaluation

by

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Executive Summary

In 1998, Dallas Area Rapid Transit (DART), a public transit agency in Dallas, Texas, began operating a large fleet of heavy-duty buses powered by liquefied natural gas (LNG). As part of a $16 million commitment to alternative fuels, DART operates 139 LNG buses serviced by two new LNG fueling stations.

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 15 of DART's LNG buses in revenue service, compared with the performance of 5 diesel buses operating on comparable routes.

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 transit bus applications.

In addition, this information should benefit decision makers by providing a real-world account of the obstacles overcome and the lessons learned in adapting alternative fuel buses to a transit site previously designed for diesel buses. It also identifies technology areas where future research and development efforts should be focused. The field study at DART was part of DOE's ongoing Alternative Fuel Transit Bus Evaluation Project.

Methods

Data were gathered daily from fuel and maintenance tracking systems for more than 1 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

The data collection was designed to cause as little disruption for DART as possible. The original evaluation fleets consisted of 10 LNG buses and 5 similar diesel buses. Five additional LNG buses were added to the evaluation after the start-up period.

Results

Some early start-up issues required the LNG buses to operate on restricted routes and schedules, but after these issues were resolved, the LNG and diesel fleets performed the work DART expected during the evaluation period.

The LNG buses emitted less nitrogen oxides and particulate matter than the diesel buses. By most other measures of operation, the diesel buses performed better than the LNG buses. The LNG buses had lower energy equivalent fuel economy, higher fuel costs per mile driven, and higher engine and fuel system maintenance costs per mile driven than the diesel buses.

Overall, the operating cost comparison was mixed. The operating costs for the original LNG buses averaged about 3% higher than for the diesel buses. The 10 original LNG buses averaged $0.799 per mile, and the diesel buses averaged $0.773, giving the diesel buses an advantage of $0.026 per mile.

However, the new LNG buses showed the lowest operating cost per mile, at $0.713—about 8% less than the diesel buses.

Lessons Learned

The LNG bus evaluation project provided DART, DOE, and other participants the opportunity to learn many lessons about alternative fuels:

- Transit agency employees should learn all they can about potential problems with alternative fuels in field operations. Agencies should plan for unexpected contingencies and exercise patience through the start-up process.
- Critical vehicle systems should undergo engineering design validation and/or performance tests before vehicles are put into service.
- Transit agencies need to be committed to success and to invest the personal energy, infrastructure, and financial resources needed to make alternative fuel programs work.
- The LNG industry needs to improve its own technology support infrastructure, and be able to respond to the needs of large fleets of LNG vehicles.
- All critical systems need to be integrated through strong communication and accurate information within the transit agency.

Obstacles Overcome

Early in the deployment of the LNG buses, DART experienced problems with operating range, fuel mileage, fuel filling, and reliability. DART also resolved problems with methane sensors, fire suppression systems, electronics, and multiplexing systems. (Some of these problems also occurred with the diesel fleet.)

Cummins resolved several problems with early failure of engine components (e.g., turbocharger, spark plugs, and wastegate). Some engine problems with the DART LNG buses persisted through the end of the study period. Design work continues on the LNG buses.

The original LNG buses were designed with a three-tank system that provided a range of only 250 miles in service (277 miles in track tests), well below DART's goal of 400 miles. At DART's request, the manufacturer, NovaBUS, added a fourth LNG tank, which provided an acceptable range of 358 miles in service (380 miles in track tests).

Other obstacles overcome included ensuring full tanks at each fueling stop, redesigning the LNG fueling nozzle to prevent leaking, exploring the use of a breakaway hose to prevent damage from driveaways during fueling, and a starter lockout switch at the fueling door.

By spring 2000, DART had resolved nearly all the problems with the LNG buses by applying the lessons learned from start-up and by cooperating with manufacturers and component suppliers. The LNG buses have operated on all routes (except a few of the longest) originating from the Northwest facility.

Future LNG Operations at DART

DART's two facilities for fueling and servicing LNG buses have room to grow. New procurements for buses have a provision for LNG buses. DART continues to evaluate the operation of its LNG fleet.

DART continues to work on optimizing the LNG bus operations. DART is working with Cummins and ZF (the transmission vendor) to raise the fuel economy 5%–10% by optimizing the shift points of the transmission and by improving engine component design. DART is also working to optimize the onboard LNG fuel tank system.

Overview

Dallas Area Rapid Transit (DART), a transit agency based in Dallas, Texas, has been operating liquefied natural gas (LNG) buses from its Northwest facility since November 1998. The LNG bus fleet now includes 139 LNG buses in service. Between February 1999 and January 2000, data on DART's LNG and diesel buses were collected for evaluation as part of the U.S. Department of Energy (DOE)/National Renewable Energy Laboratory (NREL) Alternative Fuel Transit Bus 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 transit bus applications. The report should also benefit decision makers by providing a real-world account of the obstacles overcome and the lessons learned in adapting alternative fuel buses to a site previously geared toward diesel buses. It also identifies technology areas where future research and development efforts should be focused.

This report summarizes the results of the LNG study at DART. Further technical background, research methods, data, and detailed discussions are presented in a companion document (*DART's LNG Bus Fleet Final Data Report*, NREL, June 2000).

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

Alternative Fuel Projects at DOE and NREL

On behalf of DOE, NREL (a DOE national laboratory) managed the data collection, analysis, and reporting activities for the DART LNG bus evaluation.

NREL and participating companies across the United States are evaluating several types of alternative fuels. These fuels have included LNG, compressed natural gas (CNG), biodiesel, ethanol, methanol, and propane (liquefied petroleum gas).

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 to reduce U.S. consumption of imported petroleum and to benefit users and the environment.

The Transit Bus Evaluation Project

The overall objective of the ongoing DOE/NREL Alternative Fuel Transit Bus Evaluation Project is to compare heavy-duty buses 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 transit buses have been evaluated through data collection and analysis since 1993. The transit bus program includes 15 demonstration sites and continues to add new sites for further data collection and evaluation.

Sites have been selected according to the kind of alternative fuel technology in use, the types of buses and engines, the availability of diesel comparison ("control") vehicles, and the transit agency's interest in using alternative fuels.

After analysis, peer review, and DOE approval, results from each new site are published separately.

Host Site Profile: Dallas Area Rapid Transit

The participating host site for this study was DART, a public transit agency based in Dallas, Texas. DART operates more than 1,000 buses, railcars, and vans. Its buses cover more than 130 local and express routes in a 700 square mile service area that includes Dallas and 12 suburban cities.

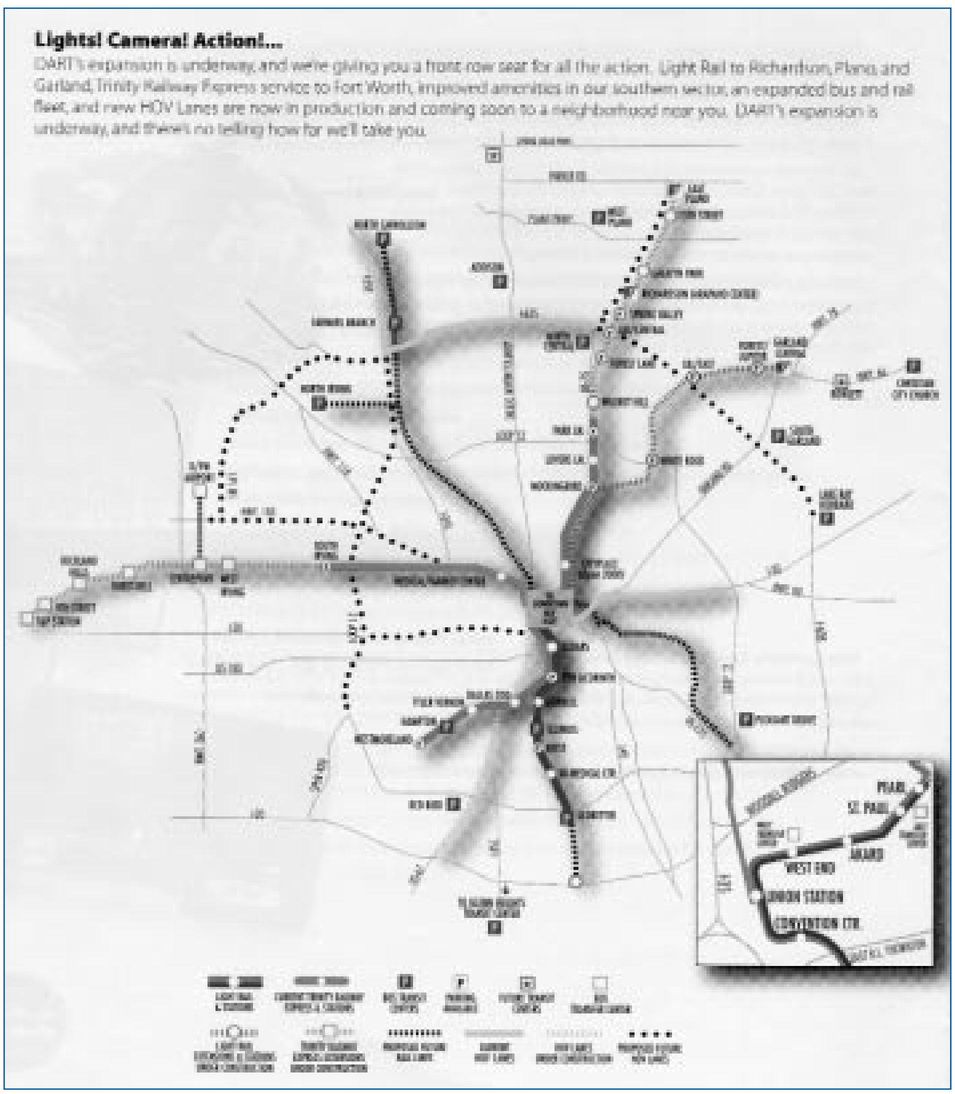
DART estimates that it serves more than 200,000 passengers daily, including rail (see Figure 1). DART is a leader in business development and environmental-minded policy, and won the 1997 Transit Agency of the Year award from the American Public Transportation Association.

DART's LNG Buses

DART's fleet now includes 139 LNG buses. The first of the 110 LNG buses ordered from NovaBUS (Roswell, New Mexico) were delivered to DART in early 1998, and began operating in November 1998. Before any buses were delivered, DART decided to increase the LNG bus order from 40 to 90 during the second year of the contract and from 20 to 40 during the third year.

Because of lower than expected range and fuel economy, DART requested that NovaBUS add a fourth LNG tank on each bus to increase the range of the LNG buses to 380 miles. (The LNG buses were originally designed with a three-tank system.) The 49 LNG buses already in Dallas were modified at DART and NovaBus installed the fourth LNG tank in the 90 LNG buses delivered after April 1999. Figure 2 shows an LNG bus at DART. Figure 3 shows one of the diesel buses evaluated.

In part because of operating range, fuel economy, and other engine-related issues, the DART contract with NovaBUS was changed in July 1999 so the last 60 LNG buses (of the 200 ordered) would be diesel.



Courtesy of DART/PIX 09175

Figure 1. **DART bus and rail operations in Dallas, Texas**

Thus, 140 LNG buses were planned in the final order. DART needed more time to resolve problems before adding more LNG buses to the fleet. DART has had great success with the program infrastructure, but the mobile side of the operations was disappointing in the beginning.

DART never accepted the first LNG bus in the order (the pilot bus) because it needed design changes. The LNG fleet at DART thus stood at 139 buses. With the addition of the fourth LNG tank on each bus, and several modifications to the fuel gauges onboard the buses and to LNG station operating procedures, the range problem was resolved by September 1999.

Courtesy of DART/PIX 09148

Figure 2. DART LNG bus on the road in Dallas, Texas

Courtesy of DART/PIX 09149

Figure 3. One of DART's diesel buses

As shown in Table 1, the 10 alternative fuel buses originally planned for evaluation in this study were model year 1998 NovaBUS RTS-style buses equipped with Cummins L10-280G engines. The 5 diesel buses used for comparison were also model year 1998 NovaBUS RTS-style buses, but they used Cummins M11-280 engines. The comparison of engines was deemed acceptable based on the similar maximum torque and horsepower of these models and on previous discussions with Cummins. Drivers reported no driving differences between the DART fleet NovaBUS LNG and the diesel buses.

The diesel buses in the evaluation started operating in May 1998. The LNG and diesel buses were used to transport passengers along all routes served by DART's Northwest facility.

To better understand fuel economy and optimized operation of the LNG buses, 5 more LNG buses were added to the evaluation. These buses had design enhancements to improve operating range and were placed into service in June 1999. (Throughout this report, the original 10 LNG buses will be referred to as the "original LNG buses;" the additional 5 buses will be referred to as the "new LNG buses.")

Table 1. Vehicle Descriptions for DART Evaluation Buses

Description	Diesel Control	LNG
Number of Buses	5	10 original, 5 new
Chassis Manufacturer/Model	NovaBUS, 40 foot	NovaBUS, 40 foot
Chassis Model Year	1998	1998, 1999
Engine Manufacturer/ Model, Year	Cummins M11-280, 1998	Cummins L10-280G, 1998
Engine Ratings Max. Horsepower Max. Torque	280 hp @ 2000 rpm 900 lb-ft @ 1200 rpm	280 hp @ 2100 rpm 900 lb-ft @ 1300 rpm
Fuel System Storage Capacity	125 gallons	4 LNG MVE, Inc. tanks, 221 LNG gallons (132 diesel equivalent gallons)
Transmission Manufacturer/Model	ZF 5HP590	ZF 5HP590
Catalytic Converter Used (Y/N)	Yes	Yes
Curb Weight (lbs)	28,740	30,920
Gross Vehicle Weight (GVW)	39,500	39,500

Unless otherwise noted, all data for LNG buses in this report are from the original set of 10 LNG buses.

The LNG buses cost about $40,000 more than the diesel buses DART ordered at the same time. The LNG buses cost approximately $330,000 each (including the fourth LNG tank); the diesel buses cost about $290,000 each.

DART's Involvement in Air Quality Improvement

DART's LNG program planning for fueling and bus ordering began in 1995. Two LNG fueling stations were planned, one at Northwest and one at South Oak Cliff. The LNG fueling station at Northwest was completed in 1998 (with modifications in 1999 to optimize automatic controls), and the station at South Oak Cliff was completed in 1999 and started operating in early 2000. Overall, DART invested approximately $16 million between 1995 and 2000 for LNG buses and facilities.

DART has a long-standing commitment to environmental improvement. In addition to the 139 LNG buses, DART operates 2 CNG buses, 20 CNG trolleys, 200 CNG paratransit vans, and 148 CNG automobiles and trucks. Overall, 41% of DART's motor fuel fleet is powered by natural gas.

Project Design and Data Collection

Data were gathered from DART'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 data from each 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 [RCs])
- Records of repairs covered by manufacturer warranty

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

DART 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 were distributed to designated staff at DART for review and input.

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

DART's Facilities and Bulk Fuel Storage

DART operates nearly 1,000 buses and vans across 700 square miles in the Dallas, Texas, metropolitan area. These buses are operated from three bus facilities:

- East Dallas Equipment Service Garage
- Northwest Equipment Service Garage
- South Oak Cliff Bus Operations Facility

Each facility operates about 200 full-size transit buses. DART also has about 250 buses maintained and operated by a contractor.

The LNG buses are stored outside or under an open-air sunscreen to reduce the heat (Figure 4). For maintenance, the enclosed facilities at Northwest and South Oak Cliff were built with LNG in mind. The heating, ventilation, and air conditioning (HVAC) were rated with enough air changes to dissipate small natural gas leaks safely. The facilities are also equipped with infrared and methane/combustible gas detectors and alarms. When the detectors measure methane at concentrations approaching the combustible range, visual and audible alarms are activated and some of the overhead doors open automatically. LNG buses are parked outside if maintenance is not completed during a work shift.

In March 1998, DART commissioned Lone Star Energy to develop an LNG fueling station at the Northwest facility. Other suppliers and vendors included Chart Industries (formerly MVE, Inc.). The facility consists of two 30,000-gallon storage tanks, three pumps rated at 60 gallons per minute (gpm) and 110 pounds per square inch gauge, and three LNG dispensers (located alongside diesel fuel dispensers).

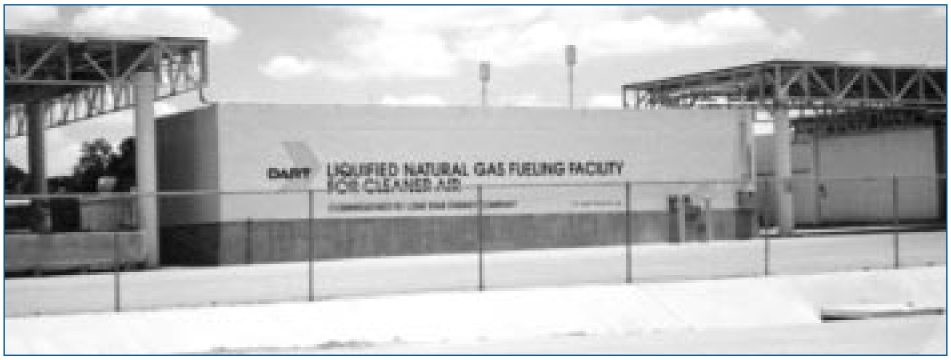
Figures 5 and 6 show the fueling station from outside the Northwest facility (no tanks showing) and inside with piping from the tanks inside the canopy over to


Courtesy of Kevin Chandler/PIX 07849

Figure 4a. DART buses parked under an open-air sunscreen at the Northwest facility


Courtesy of DART/PIX 09149

Figure 4b. DART buses parked outdoors at the Northwest facility



Courtesy of Kevin Chandler/PIX 07177

Figure 5. LNG fueling station at Northwest as seen from the street

Courtesy of Kevin Chandler/PIX 07850

Figure 6. Northwest fueling station, showing canopy where fuel lines run from tank to fueling lanes

Courtesy of Kevin Chandler/PIX 09197

Figure 7. DART fueling station receiving bulk LNG from supply

Courtesy of DART/PIX 09179

Figure 8. LNG fueling hoses connected to DART bus

the dispensers in the fueling lanes. The Northwest LNG fueling facility was designed to service a maximum of 210 LNG buses nightly. Figure 7 shows the station receiving bulk fuel from a Lone Star Energy tanker truck.

The station has a cooldown cycle that is required before LNG fueling. This cycle consists of recirculating the LNG in the piping from the fuel storage tanks to the dispensers (about 300 feet of piping) and the hose at the dispenser (about 65 feet per dispenser).

The cooldown cycle can take 12–30 minutes. The operation of the LNG fueling station is controlled from a computer at the shift manager's station in the maintenance shop. The LNG buses are cleaned and fueled at the same islands as the diesel buses (three lanes and three sets of dispensers).

The fueling process at DART begins when the bus enters the fueling island. Each bus is equipped with an electronic hubodometer that communicates directly with the Fleetwatch® tracking system at the fueling island. The Fleetwatch® system electronically records the type and amount of fuel, engine oil, and other fluids added to the bus. The data are periodically uploaded to the DART network computer system. Once fueling has begun at the Northwest station, LNG can be pumped at 50 gpm onboard the buses (see Figure 8).

A sister LNG fueling station at DART's South Oak Cliff facility was also installed by Lone Star Energy Company. It has two 20,000-gallon tanks, three pumps, and three dispensers. The station was constructed after the Northwest station, and the design was modified to incorporate lessons learned.

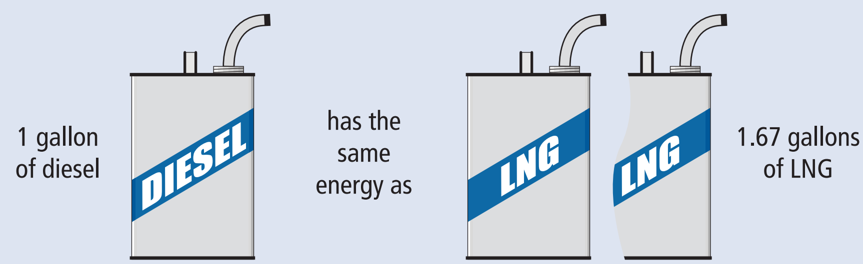
The cost for the two LNG stations and the maintenance facility modifications at Northwest and South Oak Cliff was about $7.5 million for design, construction, and start-up.

Project Start-Up at DART

The first LNG bus was delivered to DART in January 1998, and began limited operations in the Dallas region. The LNG program officially started in November 1998, when the first LNG buses began in revenue service. Early in the deployment of the LNG buses, however, DART experienced problems with operating range, fuel mileage, fuel filling, and reliability. These problems were partly related to the large size of DART's LNG fleet and the capacity of the LNG industry to respond quickly to problems in the field. In addition to engine- and fuel-related issues, DART resolved problems with methane sensors, fire suppression systems, electronics, and multiplexing systems. (Some of the same problems also occurred with the diesel fleet.)

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.



By spring 2000, DART had resolved nearly all the problems with the LNG buses by applying the lessons learned from start-up and by cooperating with manufacturers and component suppliers. The LNG buses have been operating with no restrictions on all routes at the Northwest facility, except for a few of the longest routes.

LNG Engine Issues

Cummins resolved several problems with early failure of engine components (e.g., turbocharger, spark plugs, and wastegate.) Some engine problems with the DART LNG buses persisted through the end of the study period. Cummins is addressing issues with spark plugs and wires, cylinder head design, the turbo actuator, coils, valves, and the wastegate. Design work continues to optimize the power train and increase fuel economy on the LNG buses.

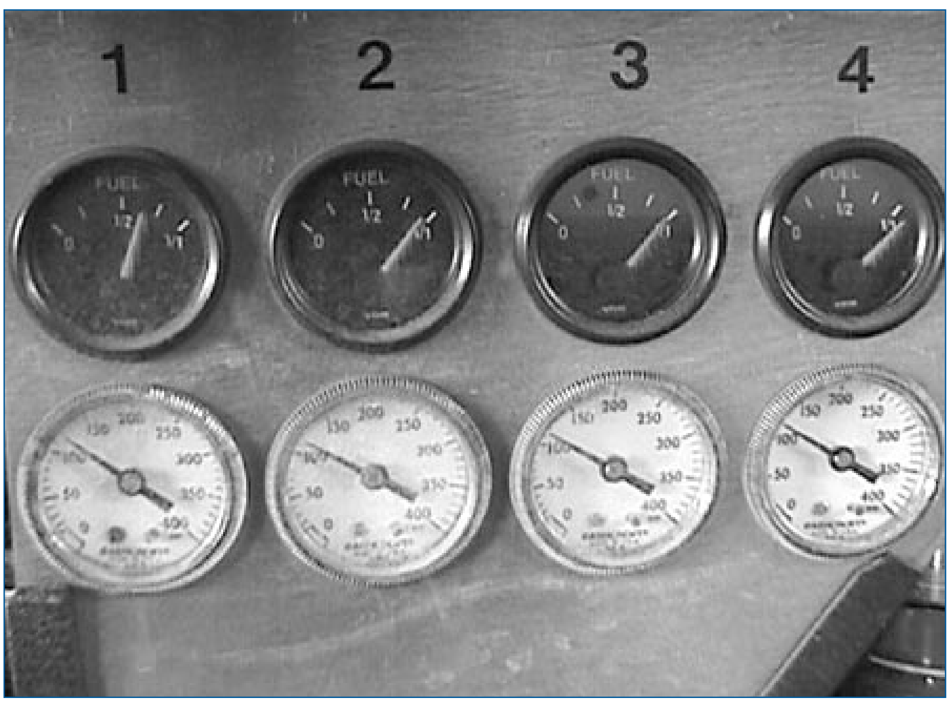
Range and Fuel Gauge Issues

DART dispatches most buses on two runs during a standard operating day, with no midday refueling. When the LNG buses first began to operate, the range was significantly lower than the required 400 miles. The expected fuel economy for the LNG buses was approximately 2.2 mpg. In service for DART, the LNG buses had a fuel economy of approximately 1.6 mpg, which is in line with the industry average for LNG buses operating in a "rough transit" duty cycle (i.e., nearly 50% idle time and very low average speed).

The LNG buses were originally designed with a three-tank system that provided 154 usable LNG gallons. At 1.62 mpg, this provided a range of only 250 miles in service (277 miles in track tests). In July 1999, DART asked NovaBUS to add a fourth LNG tank, which made the total usable LNG capacity 221 gallons. This gave the LNG buses a range of 358 miles in service (380 miles in track tests), which has been acceptable for DART's service.

The desire to maximize range required ensuring a full fill of LNG onboard the buses. Originally, the fuel level indicator could show nearly full when one fuel tank was nearly empty. This situation occurred when one LNG tank had higher pressure (higher resistance to having LNG flow in) or was "hotter" than the other tanks. This would cause the other tanks to fill first and the fuel nozzle would occasionally shut down automatically because of back pressure before filling the higher pressure tank.

To ensure all tanks were filled with fuel, a level indicator and pressure indicator for each tank were installed at the fuel fill location on each bus (Figure 9). The fueler can thus easily see whether a tank is not filled completely and can restart the fueling process. As a last resort, the fueler can start the vent filling procedure by manually opening the vent valve for each tank that is not full. Because each vent valve is on the end of a tank, the fueler may have to crawl under the bus to open and close the valve. This adds 10 to 15 minutes to the fueling process.



Courtesy of DART/PIX 09180

Figure 9. Fuel level and pressure indicators on LNG buses at DART

Other Fueling Issues

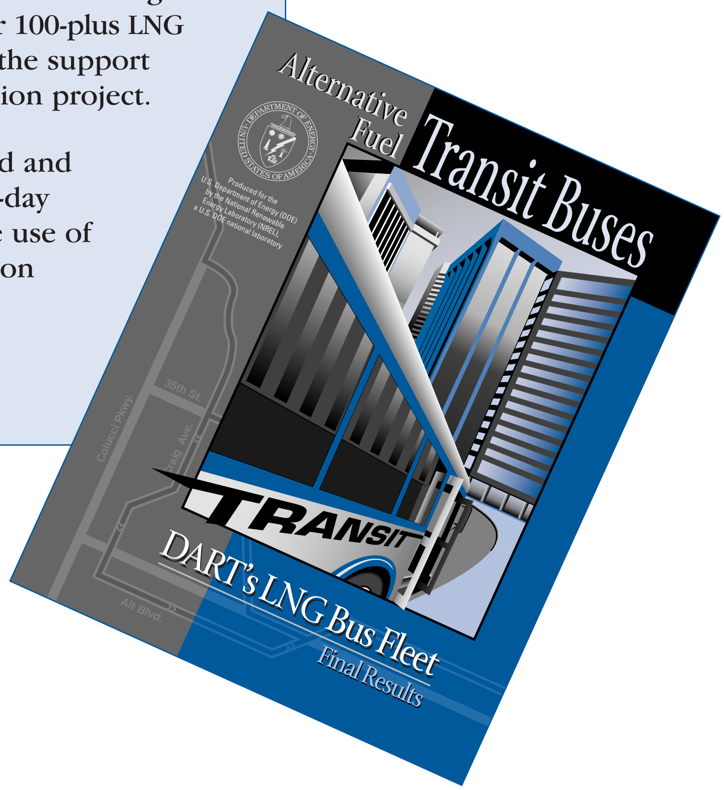
The nozzle used for transferring LNG into the bus sometimes leaked and needed to be rebuilt. Leaking causes ice to form on the nozzle, which makes connecting and disconnecting the nozzle difficult, and damages the seal on the nozzle. The nozzle was redesigned by the vendor, J.C. Carter, and by the end of data collection seemed to work better.

Another fueling issue has been the need for a breakaway fueling hose to prevent damage and fuel loss when the bus is driven away from the fuel station while the LNG hose is still connected. This occurred five times at the Northwest station, causing significant damage to the dispenser. One possible solution is to add a breakaway fitting (standard equipment in CNG, diesel, and gasoline fueling systems) to the hose. Another option is to add an electrical circuit to disable the starter on the bus when the fueling door is open.

Lessons Learned at Start-Up*

- Transit agency employees should learn all they can about the alternative fuel being introduced, the vehicles involved in the project, and potential problems with alternative fuels in field operations. Agencies should do extensive advance planning, including planning for unexpected contingencies, and exercise patience through the start-up process.
- Critical vehicle systems should undergo engineering design validation and/or performance tests before vehicles are put into service.
- Transit agencies need to be committed to success and to invest the personal energy, infrastructure, and financial resources to make alternative fuel programs work.
- The LNG industry needs to improve its own technology support infrastructure, and be able to respond to the needs of large fleets of LNG vehicles. The support required for 100-plus LNG vehicles in revenue service is far greater than the support required for a few or a dozen in a demonstration project.
- All critical systems, including engines, onboard and stationary fuel equipment, chassis, and day-to-day operations, need to be integrated through the use of strong communication and accurate information within the transit agency.

*A report that focuses on DART's start-up experience is available from the National Alternative Fuels Hotline (1-800-423-1363) or on the World Wide Web (http://www.afdc.doe.gov).



Evaluation Results

By the end of the evaluation period, both the LNG and the diesel fleets were doing the work DART expected. The major difference in operations was that early on, the period of restricted operation for the LNG buses meant that the diesel buses were operated for more miles than the LNG buses.

The LNG buses emitted less nitrogen oxides and particulate matter than the diesel buses. By most other measures of operation, the diesel buses performed better than the LNG buses. The LNG buses had a lower energy equivalent fuel economy, higher fuel costs per mile driven, and higher engine and fuel system maintenance costs per mile driven than the diesel buses.

Overall, the operating cost comparison was mixed. The operating costs for the original LNG buses averaged about 3% higher than for the diesel buses. The LNG buses averaged $0.799 per mile. The diesel buses averaged $0.773 per mile, giving the diesel buses an advantage of $0.026 per mile. The new LNG buses, however, showed the lowest operating cost per mile, at $0.713—about 8% lower than the diesel buses.

Bus Use in Transit Service

The buses and data collection periods used in this study are shown in Table 2.

The fuel and maintenance data for all vehicles were collected between the start of service and January 2000. The analyses and evaluation in this report focus on only the data periods shown in Table 2. The maintenance data periods were chosen to match similar vehicle lifetimes for the diesel and LNG buses. The vehicle lifetimes began after the first PMA and then run for about 1 year of service (except for the new LNG buses, which ran for 7 months). This was done to represent the same operational time frame for each fleet being evaluated.

The diesel and LNG buses at DART are used 6 days a week, 12 or more hours a day. Some buses also run on Sunday. Early

Table 2. Evaluation Vehicles and Data Evaluation Periods

Bus Fleet	Bus Numbers	Start of Service	Fuel Data Period	Maintenance Data Period
Diesel	4220–4224	May 1998	Feb 99–Jan 00	Jun 98–Jun 99
Original LNG	4320–4329	Nov 1998	Feb 99–Jan 00	Jan 99–Jan 00
New LNG	4502, 4513, 4535, 4536, 4539	Jun 1999	Jun 99–Jan 00	Jun 99–Jan 00

during the start of operation of the LNG buses, the reduced range caused the LNG buses to be used on only a few routes during the week and not much on the weekends. Once the range problems were resolved with the fourth LNG tank and optimization of the LNG system, all the LNG buses could be used in the same way the diesel buses were used. Once the range restriction was lifted, all buses were randomly dispatched on one or two routes. Only a few of the longest routes were restricted to diesel buses.

Average Speed

Because the LNG buses had shorter range in the beginning, they were restricted from some of the routes. Therefore, their average speed was slightly higher (14.4 mph), compared to the average speed for the diesel buses (13.7 mph). Once the fourth LNG tank was installed and optimized, the LNG buses were operated on all routes from the Northwest facility, except as mentioned. With the increased range, the LNG and diesel bues had the same average speed.

Monthly Miles Driven

The LNG buses traveled as much as 34% fewer miles each month than the diesel buses during the period of restricted operation. Figure 10 shows the monthly average mileage per bus for each fleet during the evaluation period (February 1999 through January 2000). Figure 11 shows the monthly average miles per bus. The diesel buses averaged 4,321 monthly miles per bus and the original LNG buses averaged 3,232 monthly miles

Figure 10. Monthly average mileage per bus

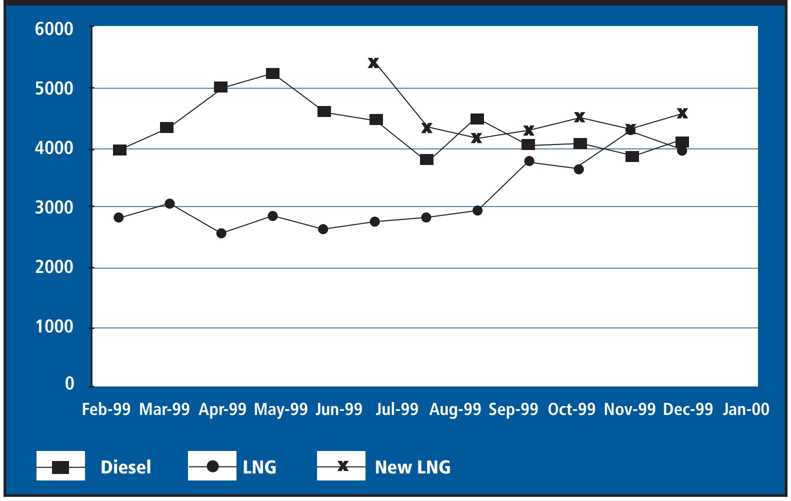
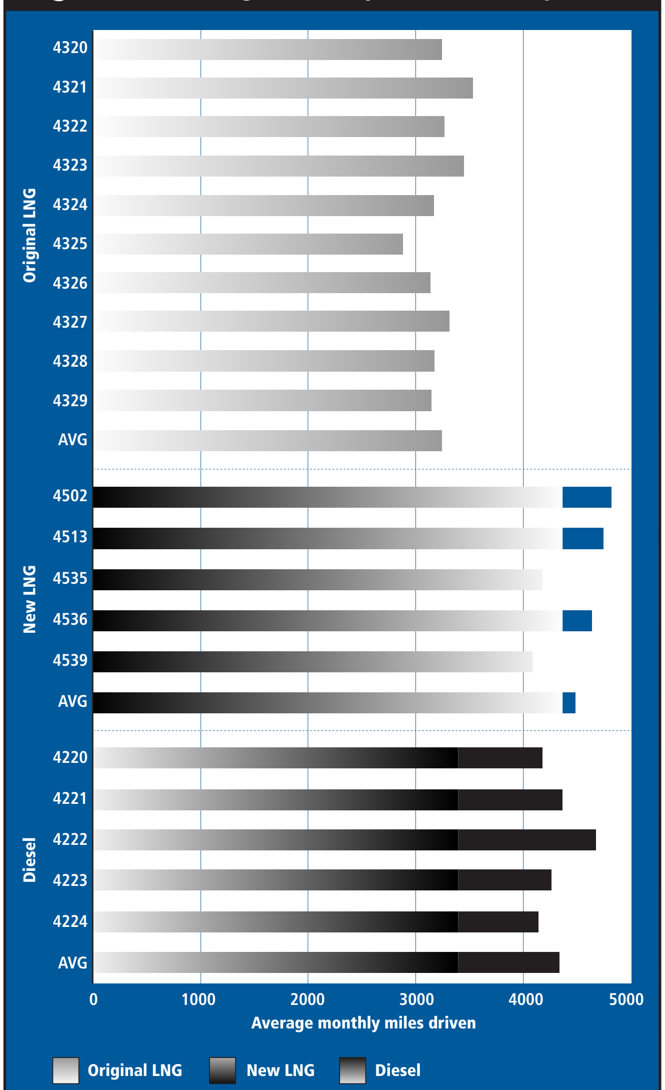
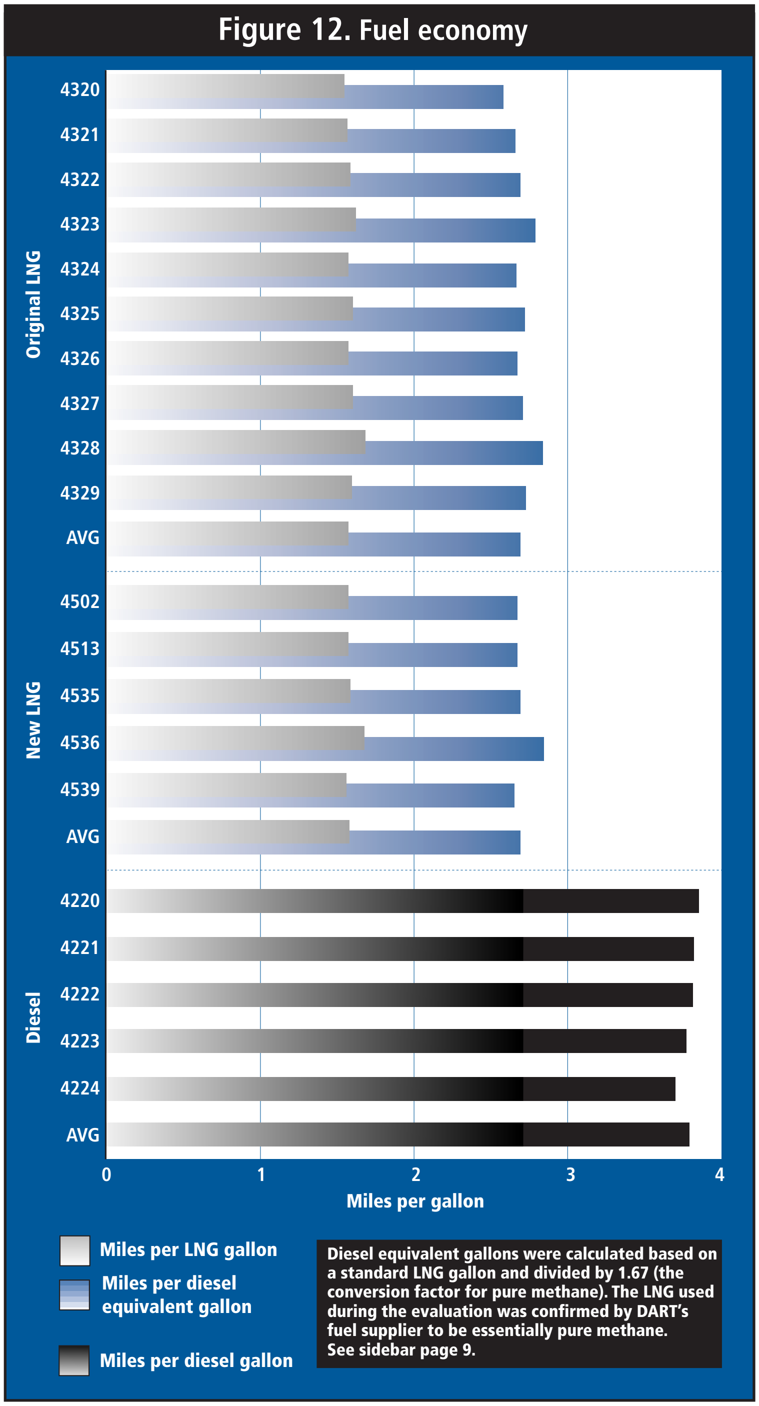


Figure 11. Average monthly miles driven per bus





per bus, 25% lower during the evaluation period. The new LNG buses had the fourth LNG tank and full range since starting operation in June 1999; hence, their average monthly miles per bus are in line with those of the diesel buses at 4,486 miles. The original LNG buses had a lower range than the diesel buses and saw lower vehicle usage until September 1999 when the fourth LNG tank was installed. After September 1999, the original LNG bus monthly mileage quickly increased to the level of the diesel buses.

Fuel Economy, Maintenance, and Costs

The LNG buses used more fuel per mile, so even though the LNG fuel cost was lower (on an energy equivalent basis) than the comparable diesel fuel, fuel cost for DART was 32% more per mile for the LNG buses than for the diesel buses in the evaluation.

Fuel Economy

Figure 12 shows the fuel economy for the diesel, original LNG, and new LNG buses. A diesel equivalent gallon is the quantity of LNG that contains the same energy as 1 gallon of diesel fuel. Diesel equivalent gallons have been calculated based on a standard LNG gallon divided by 1.67, the conversion factor for pure methane. LNG at this site is essentially all methane (at least 98%, as required by contract), according to the fuel supplier, Lone Star Energy.

On average, the LNG bus fuel economy was 28% lower than the diesel bus fuel economy on a diesel equivalent gallon basis.

Based on past experience with natural gas vehicles in heavy-duty transit operation, the fuel economy difference is within the expected range of 15% to 30% lower. The newer LNG buses with four LNG tanks had the same average fuel economy as the evaluation LNG buses.

Fuel economy measurements made at DART as part of the emissions testing on a chassis dynamometer (described in detail in Appendix H of *DART's LNG Bus Fleet Final Data Report*, June 2000) show average LNG bus fuel economy of 14% lower than the average diesel bus fuel economy on an energy equivalent basis over the Central Business District (CBD) driving cycle. This is substantially better than the 28% difference seen in actual operation.

The driving cycle for the buses has been different in service than that tested by West Virginia University (WVU) for emissions. Also, air conditioning was not running during the WVU testing and there was little idle time during the emissions testing. In service, the diesel and LNG buses typically spend 50% or more of the time idling with their air conditioning running. The natural gas engines are spark-ignited and have higher fuel consumption at idle/low speed than the diesel (compression-ignition) engines.

Fuel Cost per Gallon

Diesel fuel costs rose significantly during 1999, from $0.70 (February 1999) to $1.09 per gallon in January 2000. The average diesel fuel cost used for the evaluation was $0.90 per gallon. The average cost for LNG fuel used for the evaluation was $0.49 per LNG gallon ($0.82 per diesel equivalent gallon).

Fuel Cost per Mile

Fuel consumption cost for the LNG buses was 32% higher than for the diesel buses—LNG was $0.314 per mile and diesel was $0.238 per mile. The fuel costs, coupled with the difference in energy equivalent fuel economies, make up the fuel cost per mile. Fuel costs in the future for diesel and LNG could be different than the average fuel costs used in this evaluation, depending on changing fuel prices and changes in LNG vehicle fuel efficiency.

Engine Oil Consumption and Cost

The DART LNG buses consumed 2.03 quarts of engine oil per 1,000 miles; the diesel buses consumed 18% less (1.72 quarts per 1,000 miles).

Engine oil cost for the LNG engines was 31% higher per quart than for the diesel engines—$0.85 per quart for the LNG engines and $0.65 per quart for the diesel engines. The higher cost oil for the LNG engines is due to the low ash content specified by Cummins and the low volume purchase of this oil by DART.

The oil cost per 1,000 miles for the diesel engines was $1; for the LNG engines it was $2. However, per-mile engine oil consumption costs were very low compared to fuel and maintenance costs.

Factors Affecting Maintenance Costs

Maintenance costs for the DART evaluation were affected by several unusual factors, most notably that the NovaBUS vehicles were the first new buses purchased by DART in more than 10 years, and the first DART ever ordered from that manufacturer. Thus, the maintenance staff had to adapt to a number of new technologies in the diesel and LNG buses. New systems such as multiplexing of controls onboard the bus (instead of using hard wiring), computer-controlled engine and transmission technologies (both new to DART), antilock brake systems, and a new axle model were some of the systems DART engineers and maintenance staff had to learn and troubleshoot in a short time (see Figure 13). Added to these technologies and procedures were the LNG fuel systems, which were new to DART's transit bus operation.

Courtesy of DART/PIX 09176

Figure 13. **DART maintenance staff inspecting LNG fuel system**

Phasing the arrival of the new buses also affected maintenance cost values. The diesel buses were put into service 6 months before the LNG buses. Therefore, the troubleshooting and adjustments for the diesel buses occurred earlier on the "learning curve" for the DART staff. Issues that were resolved with NovaBUS and component suppliers during the first months of diesel bus operation resulted in lower maintenance costs for the LNG buses, because the changes had already been put in place, or because the time required to make adjustments was reduced. Similarly, the cost for troubleshooting the 5 new LNG buses was lower than for the original 10.

Maintenance Costs by Vehicle System

Figure 14 shows the relative share of the major systems contributing to maintenance costs. The portion of the maintenance costs for engine- and fuel-related systems was 8% higher for the LNG buses than for the diesel buses.

The top four categories ranked by cost are the same for the diesel, original LNG, and new LNG buses:

1. Cab, body, and accessories (includes body repairs, repairs following accidents, glass, painting, cab and sheet metal repairs, seats, accessory repairs (such as radios), farebox, and hubodometer)
2. Engine- and fuel-related (includes exhaust, fuel, engine, non-lighting electrical, air intake, and cooling repairs)

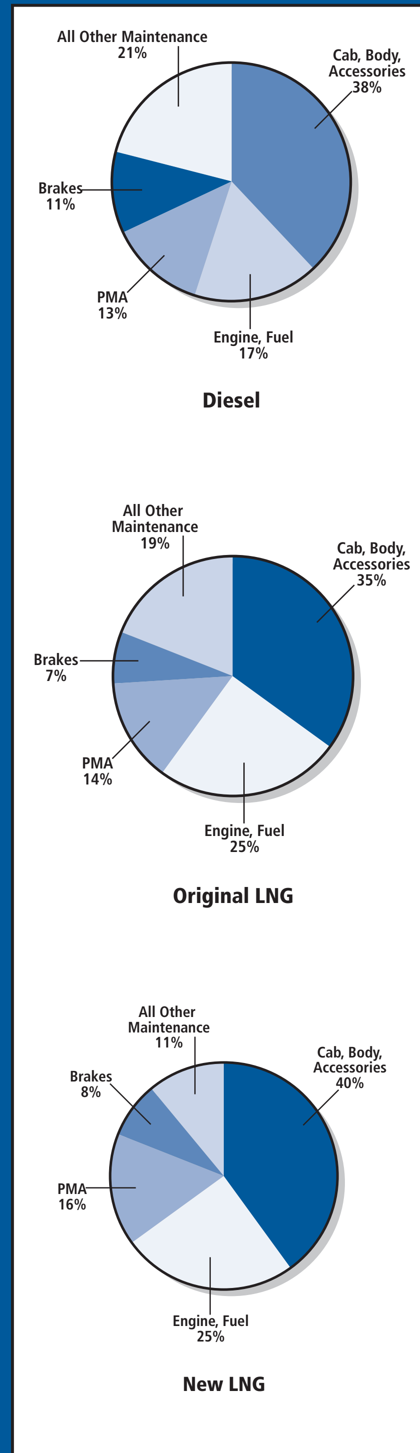
3. PMA inspection (includes only labor for inspections during preventive maintenance)
4. Brakes

The diesel bus maintenance costs were higher than expected for systems unrelated to the engine- and fuel-related systems. Only the engine- and fuel-related systems would be expected to show differences between the LNG and diesel buses. In this case, several systems unrelated to the drivetrain required significant maintenance for the diesel buses. In the following discussion, only the per-mile results from the similar vehicle lifetimes are covered.

Brief summaries of the differences seen between the diesel and LNG fleets, and some of their causes, are as follows:

- Cab, body, and accessories systems – Diesel bus maintenance costs were about 17% higher because of problems with accessories such as surveillance equipment.
- Engine- and fuel-related systems – The original LNG buses had maintenance costs 33% higher than the diesel buses; the new LNG buses 10%. The new LNG buses had a lower maintenance cost difference than the original LNG buses because of lower labor costs for troubleshooting.
- Exhaust system – The maintenance costs were 59% lower for the original LNG buses and 80% lower for the new LNG buses than for the diesel buses.
- Fuel system – The LNG maintenance costs were much higher than the diesel buses (3 times higher for the original LNG buses and 2.4 times higher for the new LNG buses). Most LNG bus maintenance for the fuel system was for labor to troubleshoot problems such as low power and fuel leaks.
- Engine system – Costs were about 40% higher for the original LNG buses and 3% lower for the new LNG buses.
- Non-lighting electrical systems – Costs were 39% higher for the original LNG buses and 56% higher for the new LNG buses. The parts and labor costs were higher. Most parts costs for the original LNG buses were due to spark plugs and wires changed as part of preventive maintenance.
- Air intake system – The costs were low and nearly the same for the diesel and the original LNG buses. For the new LNG buses, the cost was about half that of the diesel buses.
- Cooling system – The costs were nearly the same for the diesel and the original LNG buses. For the new LNG buses, the cost was about half that of the diesel buses.
- PMA inspections – As expected, costs were essentially the same for the study fleets. There should be no extra costs for inspections on any of the study fleets, because the vehicles were in approximately the same service.
- Brake system – Both study fleets of LNG buses had about the same costs for brake system maintenance. The diesel buses required more labor to troubleshoot the antilock brake systems.

Figure 14. Share of maintenance costs across major systems



- Lighting system – The maintenance costs were about 34% lower for the original LNG buses and 70% lower for the new LNG buses than for the diesel buses.
- Tire systems – All tire costs were covered under a lease arrangement, with a consistent cost of $0.0051 per mile for tire replacements.
- Transmission – The maintenance costs were about 73% higher for the original LNG buses and 55% lower for the new LNG buses than for the diesel buses. The original LNG buses had higher costs because of higher parts costs and occasional unscheduled maintenance.
- HVAC systems – The original LNG buses had maintenance costs 12% lower than the diesel buses; the new LNG buses 76% lower. The diesel and original LNG buses required significant labor hours for troubleshooting problems with the air conditioning motors and problems that were mostly covered under warranty.
- Air system – Most repairs for the air system are assigned to the brakes, door, and suspension systems. These were low overall but slightly higher for the diesel buses.
- Frame, steering, and suspension systems – The diesel bus maintenance costs were nearly double those for the LNG buses. These higher costs were caused mostly by bumper module replacements due to minor accidents and labor for problems with radius rod replacements covered by the warranty.
- Axle, wheel, and drive shaft systems – Maintenance costs for the study buses were low.

Roadcalls

An RC is defined in this report as an on-road failure of an in-service transit bus that requires a replacement bus to be dispatched to complete the route. If the failed bus is fixed on the road and put back into service immediately, this is not considered an RC.

Figure 15 shows average miles between RCs for the diesel and LNG buses for all data. This chart shows that the trend for each study fleet is upward and indicates the progress DART has made toward troubleshooting and resolving start-up problems.

The low miles between RCs for the diesel buses were caused by systems other than the engine- and fuel-related systems, and the LNG buses have had many more engine- and fuel-related issues. For engine- and fuel-related systems, both sets of LNG buses had miles between RC results that were 50% lower than the diesel buses.

Warranty Costs

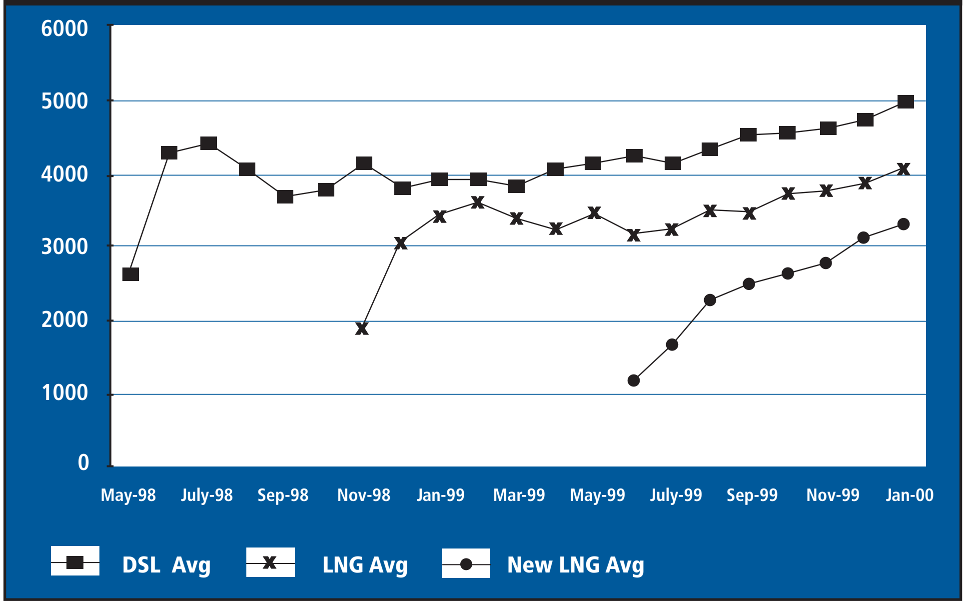
On a cost per bus basis across all data collected, the diesel buses had the highest costs for warranty repairs ($17,101.54). The per-bus costs were lower for the original LNG buses, at $10,660.65. The new LNG buses had the lowest per-bus costs, at $8,674.57.

This trend is consistent with DART and NovaBUS working through the maintenance problems of the buses as they arrived. In this analysis the diesel buses were put into service 6 months before the first LNG buses and a year before the new LNG buses.

The highest warranty cost systems for each fleet were as follows:

- Diesel – body, cab, accessories; HVAC; non-lighting electrical; axles, wheels, drive shaft; and frame, steering, and suspension
- Original LNG – engine/fuel-related; body, cab, accessories; non-lighting electrical; HVAC; fuel; and axles, wheels, and drive shaft
- New LNG – body, cab, accessories; non-lighting electrical; exhaust; and engine/fuel related

Figure 15. Average miles between RCs for diesel, original LNG, and new LNG buses (does not include out-of-fuel RCs)



Overall Maintenance Costs

The following analysis covers total maintenance costs for similar vehicle lifetime periods with no warranty work included. Similar vehicle lifetimes were chosen to represent the period beginning after the first PMA and running for about 1 year. Focusing on only the similar vehicle lifetime results, the vehicle usage has been 17% higher for the diesel buses.

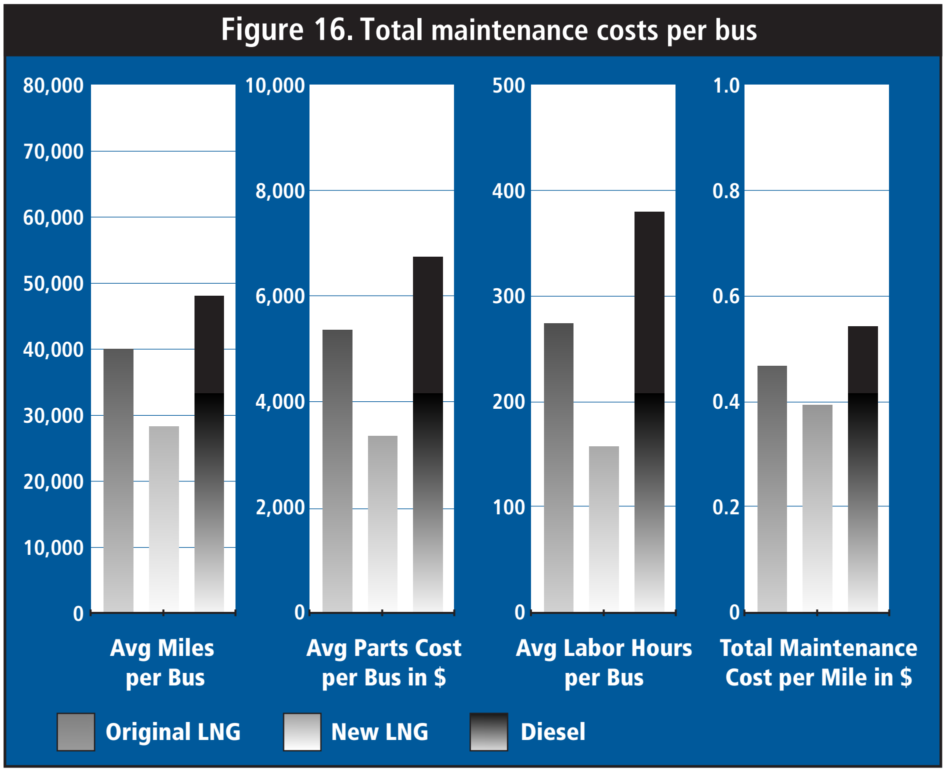
Figure 16 shows the total maintenance costs per bus across the original LNG, new LNG, and diesel fleets evaluated. The original LNG buses showed significantly lower parts costs per bus than the diesel buses. The labor hours were also lower for the original LNG buses. (Labor costs were calculated using a constant average rate of $50 per hour.)

The original LNG buses had a total maintenance cost per mile 9% lower than the diesel buses. This difference was caused by maintenance of accessory systems. Engine- and fuel-related systems maintenance costs were significantly higher for the original LNG buses, as discussed earlier.

Total maintenance costs per mile for the new LNG buses were much lower than for the diesel buses. These costs were lower because in the accessory systems many of the problems with the diesel buses were resolved for the LNG buses. Also, the preventive maintenance costs were lower because the data evaluation period was shorter than the full year used for the diesel and original LNG bus evaluation.

Overall Operating Costs

Figure 17 provides a summary of operating costs for the diesel, original LNG, and new LNG study groups of buses. These results are only for the similar



vehicle lifetime data periods. Total operating costs include fuel and maintenance costs, and exclude driver labor. Engine oil costs were low (maximum $0.002 per mile).

Overall, the three fleets analyzed had very similar operating costs, ranging from a low of $0.713 per mile for the new LNG buses to $0.773 for the diesel buses, and to a high of $0.799 for the original LNG buses.

This means that the original LNG buses had operating costs 3% higher than the diesel buses. The new LNG buses had operating costs 8% lower than the diesel buses. The total maintenance costs were higher for the diesel buses as explained earlier; however, for the engine- and fuel-related systems, the original LNG buses had costs 33% higher, and the new LNG buses had costs 10% higher than the diesel buses.

In Calculating the Overall Operating Costs:

- Vehicle and fueling station capital costs and driver labor were not included
- Actual fuel costs during the study were used:
  - Diesel: $0.90 per gallon
  - LNG: $0.85 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

Emissions Testing Results

Emissions tests on the diesel and original LNG buses were conducted by the WVU Department of Mechanical and Aerospace Engineering using one of its transportable heavy-duty chassis dynamometer emissions laboratories. (These laboratories were developed under DOE sponsorship.) WVU used the CBD speed-versus-time cycle to evaluate each bus.

Tests were conducted in February and March 1999. Results are shown in Figure 18. The LNG buses had less of all four regulated emissions than the diesel buses. The LNG buses were much lower in carbon monoxide and particulate matter emissions than the diesel buses. Although the nitrogen oxide emissions were quite variable, on average, the LNG buses had 17% lower nitrogen oxide emissions than the diesel buses. The LNG buses also had significantly lower non-methane hydrocarbons than the diesel buses (assumed to be non-methane). Both fleets were equipped with oxidation catalysts.

In general, the diesel buses had relatively low emissions results because oxidation catalysts were used. However, the LNG bus emissions were still significantly lower than those of the clean diesel buses.

The average miles per diesel equivalent gallon obtained during emissions testing for the LNG buses were much higher than the result obtained from in-use fuel economy data. As discussed in the fuel economy section, however, the CBD cycle used in emissions testing differed from the actual revenue service duty cycle for the diesel and LNG buses. In addition, the CBD cycle does not take into account periods of idling with auxiliary loads such as air conditioning.

Figure 17. Overall operating costs per mile in $

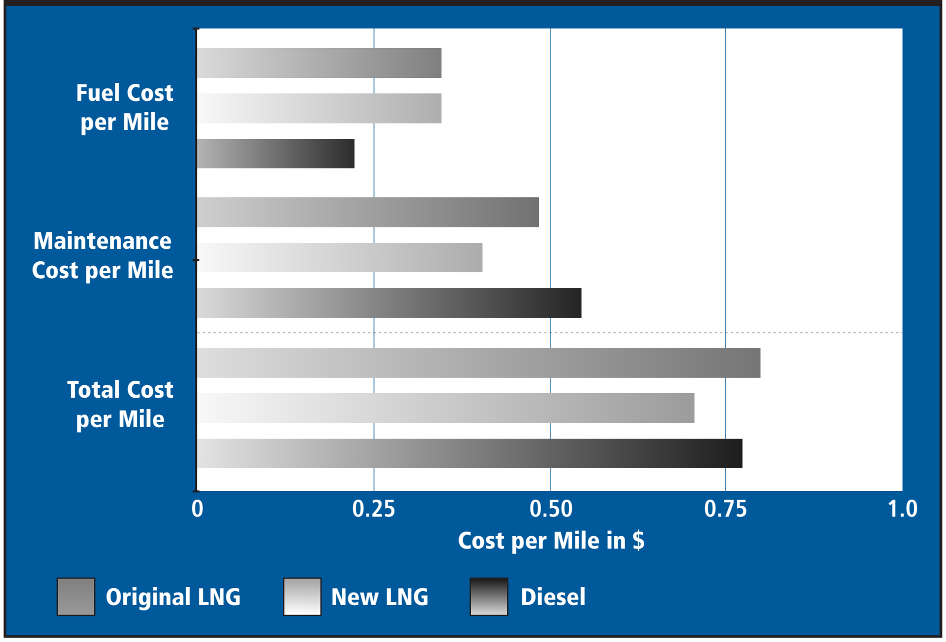
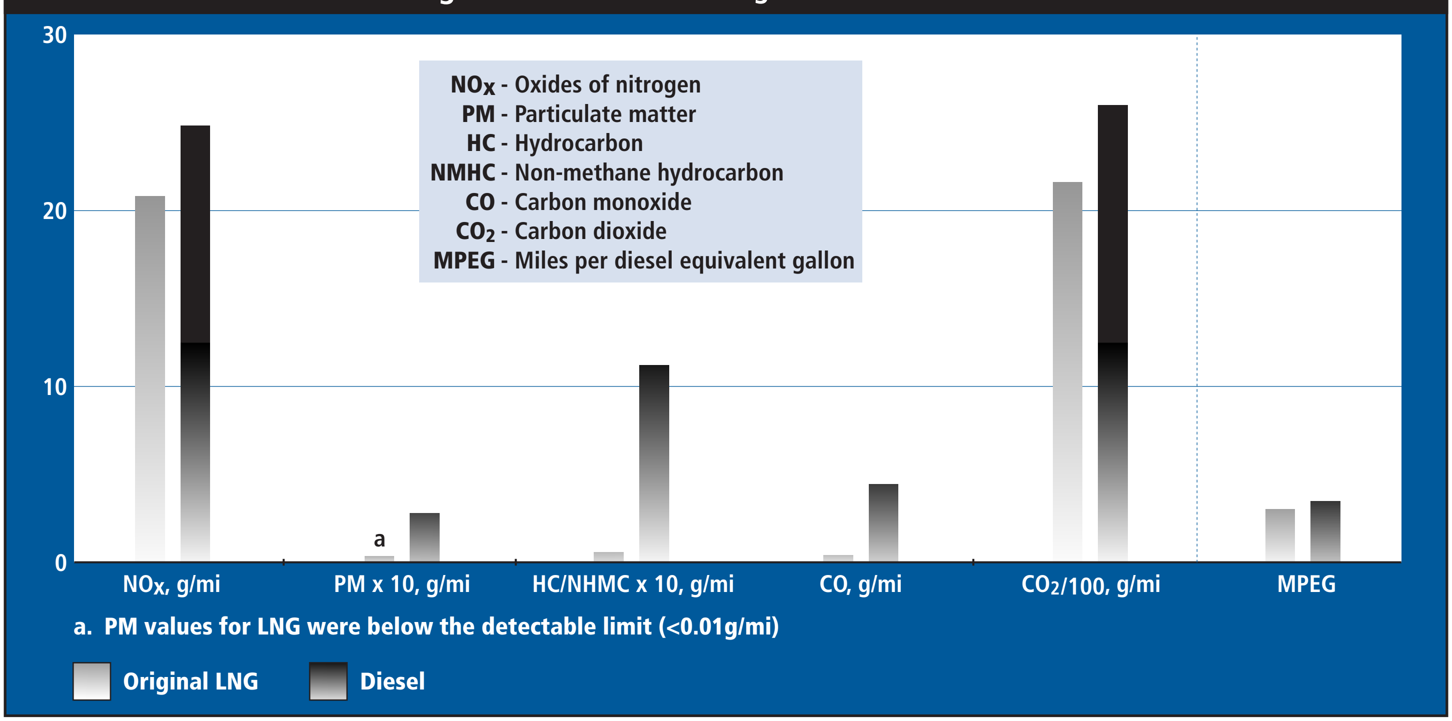
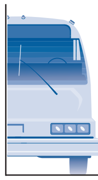


Figure 18. Emissions testing results



a. PM values for LNG were below the detectable limit (<0.01g/mi)



LNG Technology Progress in Transit

LNG transit bus technology was evaluated in the original DOE/NREL evaluation report from 1996 (*Alternative Fuel Transit Buses, Final Results from the National Renewable Energy Laboratory Vehicle Evaluation Program*). In this report, LNG transit buses were studied at Houston Metro (Houston, Texas) and Tri-Met (Portland, Oregon). One conclusion was that, because the LNG technology evaluated at these sites was considered early development equipment, another LNG site evaluation was needed to investigate operating costs and reliability on more mature LNG fuel system technology that did not use a cryogenic pump onboard the bus. Houston Metro used the Detroit Diesel (DDC) 6V92TA PING (pilot injection natural gas) dual-fuel (natural gas and diesel fuel together) engine for LNG operations. This engine is no longer available from DDC, and Houston Metro has phased most of them out. Tri-Met used the Cummins L10-240G engine for LNG operations. This engine used open loop natural gas fuel system technology, and is no longer available from Cummins.

The LNG technology being planned at DART was the newest available in the industry using the Cummins L10-280G engine and a fuel system from MVE, Inc.,

Table 3. Vehicle Descriptions for LNG Evaluation Buses

Description	Houston Metro	Tri-Met	DART
Number of LNG Buses	10	10	10
Chassis Manufacturer/Model	Mercedes, 40 foot	Flxible, 40 foot	Nova Bus, 40 foot
Chassis Model Year	1992	1993	1998, 1999
Engine Manufacturer/Model	DDC 6V92TA PING	Cummins L10-240G	Cummins L10-280G
Engine Ratings Max. Horsepower Max. Torque	 277 hp @ 2100 rpm 840 lb-ft @ 1200 rpm	 240 hp @ 2100 rpm 750 lb-ft @ 1300 rpm	 280 hp @ 2100 rpm 900 lb-ft @ 1300 rpm
Fuel System Storage Capacity	70 gallons 43 gallons diesel	174 gallons LNG	221 gallons LNG
Transmission Manufacturer/Model	Allison, HTB-748	Voith, D-863 ADR	ZF 5HP590
Catalytic Converter Used (Y/N)	No	Yes	Yes
Curb Weight (lbs)	30,560	30,030	31,000
Gross Vehicle Weight (GVW)	39,500	39,500	39,500

without a cryogenic pump. Both the engine and the fuel system had been used in several vehicle applications. DART also chose to buy diesel buses that would match the LNG technology buses almost identically, excluding the engine and the fuel system. This section investigates how the DART LNG results compare to the earlier technology at Houston Metro and Tri-Met. Table 3 shows a summary of vehicle descriptions for Houston Metro, Tri-Met, and DART LNG buses.

Roadcalls

Figure 19 shows mileage between RCs for Houston Metro, Tri-Met, and DART during the evaluation period. The first set of bars shows RCs for all systems (including the door, wheelchair lifts, and other features); the second set is for the engine- and fuel-related systems (engine, fuel, non-lighting electrical, air intake, and cooling). In the early LNG fleets at Houston Metro and Tri-Met, the diesel buses traveled significantly further between RCs. At DART, the distance between RCs was essentially the same for the diesel and the LNG buses. The engine- and fuel-related systems results show that the DART LNG buses ran a much longer distance between RCs than the Houston Metro or Tri-Met LNG buses. However, these systems resulted in more RCs for LNG than for diesel at all three sites.

Maintenance Costs

Figure 20 shows total operating costs by vehicle group at DART, Tri-Met, and Houston Metro. For engine- and fuel-related systems maintenance (the bottom portion of the stacked bars), costs for the Houston Metro LNG buses were 3.8 times (280%) higher than for the diesel buses at Houston Metro. At Tri-Met, engine- and fuel-related maintenance costs for the LNG buses were 1.6 times (60%) higher than for the diesel buses. At DART, the engine and fuel-related maintenance costs

Figure 19. Miles between roadcalls

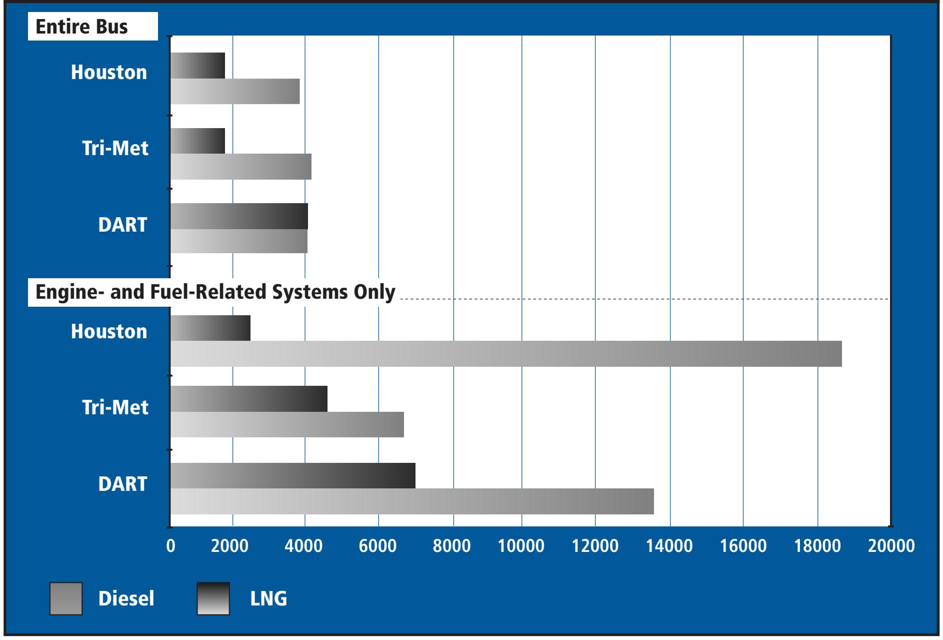
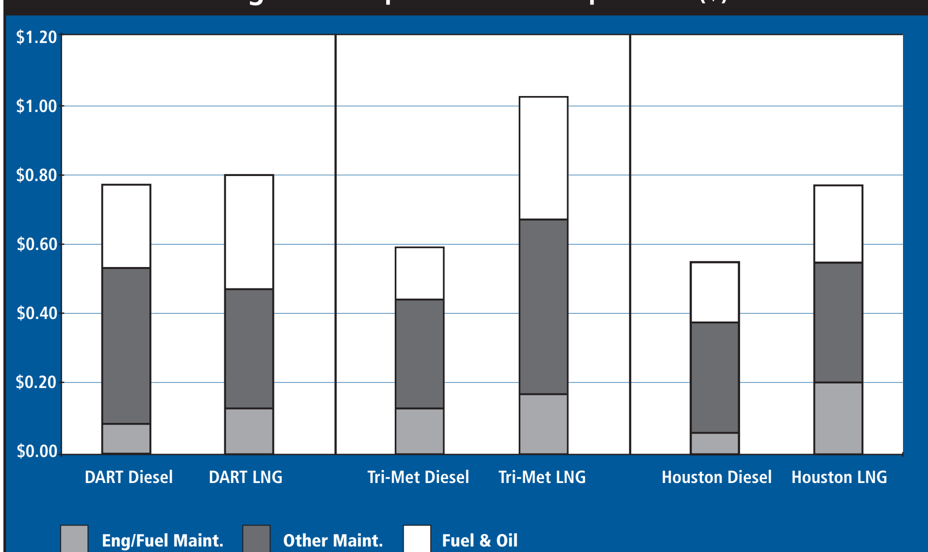


Figure 20. Operational costs per mile ($)



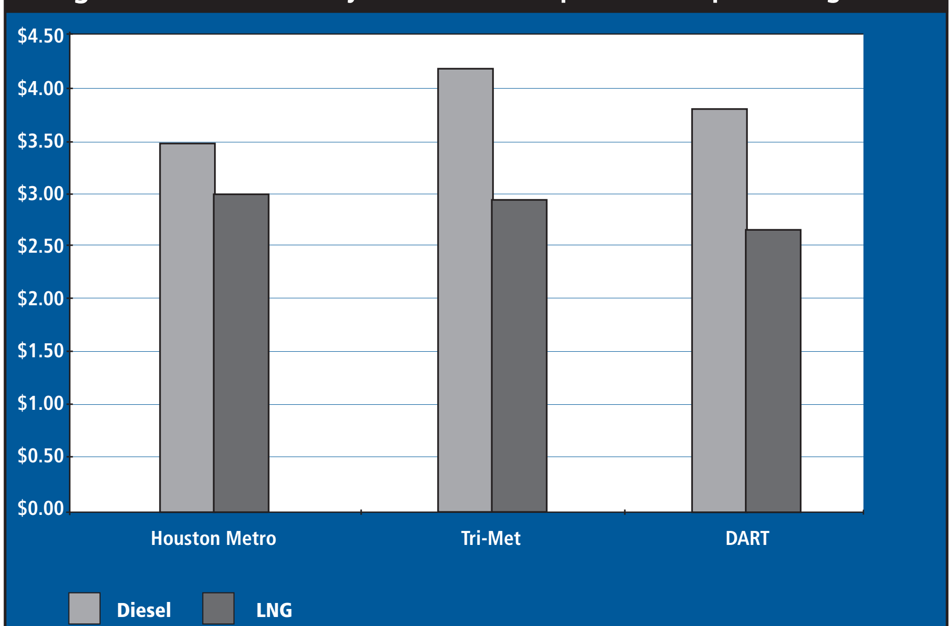
were only 1.3 times (33%) higher than for the diesel buses. (The maintenance data for all three sites were calculated with a constant labor rate of $50 per hour. For the 1996 report, $25 per hour was used.) The engine- and fuel-related maintenance costs for LNG buses were significantly lower at DART than at Houston Metro or Tri-Met.

The overall maintenance costs at Houston Metro and Tri-Met were significantly higher for the LNG buses than for the diesel control buses. At DART, the LNG and diesel bus maintenance costs were comparable.

Fuel Economy

Figure 21 shows fuel economy results for Houston Metro, Tri-Met, and DART for the LNG and diesel buses at each site. Houston Metro LNG buses showed a 13% lower fuel economy on a diesel equivalent gallon basis. The Houston Metro LNG buses had the best fuel economy, but the dual-fuel LNG/diesel buses were not operated in LNG mode often. The dual-fuel buses could operate on diesel only, and were rarely used in the dual-fuel mode. There were problems with the dual-fuel operation of the LNG buses at Houston. The Tri-Met LNG buses had a fuel economy 30% lower than the diesel buses at Tri-Met. This result is consistent with the DART LNG buses having a fuel economy 28% lower than the diesel buses at DART. However, this is a similar fuel economy difference for an LNG bus with a higher horsepower engine (240 hp at Tri-Met and 280 hp at DART).

Figure 21. Fuel economy results in miles per diesel equivalent gallon



Emissions Testing Results

For emissions testing results from WVU's mobile chassis dynamometer, results from early natural gas engines were generally erratic because of the open loop fuel control design. This was true for Houston Metro and Tri-Met LNG buses. For the spark-ignited Cummins engine at Tri-Met, the LNG buses showed extremely low particulate matter results (0.02 to 0.03 g/mi compared to the diesel buses that averaged 1.96 to 2.18 g/mi). Carbon dioxide emissions were about the same for the LNG and diesel buses (2430 g/mi). However, carbon monoxide and nitrogen oxide could be low for the LNG buses, but could also be very high. On average, the carbon monoxide results for the LNG buses were about the same as the diesel buses (10 g/mi), but were as low as 0.01 g/mi and as high as 58.8 g/mi. On average, the older technology nitrogen oxide results for the LNG buses were about 20% higher than the average for the diesel buses (41 to 45 g/mi for diesel buses), but were as low as 31 g/mi and as high as 67 g/mi. The wide swings in emissions results were attributed to the tune of the engine or improperly functioning fuel control on the LNG buses.

For the DART LNG and diesel buses on the CBD cycle, the emissions results were much more consistent and generally lower for the LNG buses. The LNG buses at DART had an average of 0.23 g/mi for carbon monoxide, 21.3 g/mi nitrogen oxide, and particulate matter that was lower than the detectable limit of WVU's equipment, <0.01 g/mi. The diesel buses at DART were much cleaner than earlier diesel bus emissions: 4.44 g/mi for carbon monoxide, 25.5 g/mi nitrogen oxide, and 0.32 g/mi for particulate matter.

Summary

Generally, the results of the DART LNG bus evaluation show that emissions, reliability, and maintenance costs have improved significantly from earlier LNG bus designs evaluated in the 1996 study. Overall bus reliability and maintenance costs were comparable with diesel. The reliability and maintenance costs for the engine- and fuel-related systems have improved compared with diesel technology, but are not yet at the same level.

Summary and Conclusions

Based on the evaluation of the DART LNG transit buses, we can conclude several major points:

- DART has had significant problems, especially related to range, with start-up of LNG operations. The buses were specified to have a 400-mile range and could achieve only 277 miles. A fourth LNG tank was added for onboard storage of LNG. This fourth tank provided enough fuel to achieve a range of 380 miles, which DART deemed acceptable. Several other problems with early failure of engine components (turbocharger, spark plugs, exhaust valve, and wastegate), fuel system (leaks), the fueling station nozzle, and other systems have nearly all been resolved through a team effort at DART and with the vendors.
- As of the end of the study period, the LNG buses were being treated the same as the diesel buses in meeting the daily pullout requirements.
- The drivers report that the LNG buses are well matched in performance to diesel; drivers have difficulty telling the buses apart.
- The fuel economy has been steady at 1.62 miles per LNG gallon or 2.70 miles per diesel equivalent gallon. DART, ZF, and Cummins continue to explore ways to increase fuel economy by 5% to 10%.
- Some engine problems continue to cause difficulties for the DART LNG buses. Cummins is still working on these problems even though the L10 engine has been discontinued as a commercial product. The resolution of problems with the L10 is applicable to the C8.3G, Cummins' current heavy-duty natural gas engine for the transit market. Cummins is addressing issues with spark plugs and wires, cylinder head design, turbo actuator, coils, and wastegate.
- Emissions testing results from WVU showed that the diesel engines at DART were very clean. The LNG emissions were cleaner yet. This emissions testing at DART was a state-of-the-art comparison for transit with 1998 technology.
- Total operating costs for the LNG buses were only 3% higher than the diesel buses. However, the maintenance costs for the engine- and fuel-related systems were 33% higher for the LNG buses than for the diesel buses. The fuel costs were 32% higher for the LNG buses than for the diesel buses.
- Miles between RCs for the LNG and diesel buses overall were about the same. The LNG buses had 50% fewer miles between RCs for the engine- and fuel-related systems compared to the engine- and fuel-related system RCs on the diesel buses.

- The problems with range and the size of the LNG fleet at DART challenged the LNG and natural gas vehicle industries. A consortium of industry partners on an "LNG task force" overcame the problems. At the end of the study, all 139 LNG buses were making pullout nearly every day.
- The two LNG fueling stations are working well for DART. Some problems have been experienced with fueling nozzle leaks and driveaways with damage to the dispensing system. The nozzle has been redesigned and seems to be managing leaks better. DART is still exploring breakaway fitting and hose designs. The new LNG station at South Oak Cliff does not have the extensive length of piping (300 feet) from the storage tanks to the fueling island that Northwest has. This has resulted in a much higher available fueling rate, as high as 70 gpm.
- In 1996, DOE/NREL published an evaluation report on LNG transit bus technology that included buses at Houston Metro and Tri-Met. The technology was considered early development equipment, and the report concluded that another LNG site evaluation was needed to investigate the operating costs and reliability on more mature LNG fuel system technology. DART was chosen as the site because the technology then being planned there was the newest in the industry.
- The results of the DART LNG bus evaluation show that emissions, reliability, and maintenance costs have generally improved from earlier LNG bus designs. The overall reliability and maintenance costs were comparable with diesel; these same costs for the engine- and fuel-related systems have improved compared with diesel technology, but are not yet at the same level.

Future LNG Operations at DART

The South Oak Cliff facility will house and maintain nearly half the current LNG fleet. Fifty LNG buses were moved to South Oak Cliff in May 2000, and the new LNG fueling facility there is operational. Both the Northwest and South Oak Cliff operations facilities have room to increase their LNG fleets.

New procurements for buses at DART have a provision for LNG buses. DART continues to evaluate the operation of its LNG fleet.

DART continues to work on optimizing the LNG bus operations.

One issue for LNG operations is that DART has invested $16 million for buses and facilities. The two LNG fueling stations have significant capacity left: 139 LNG buses of a maximum 350 LNG buses that could be filled nightly, or 40% of capacity. DART has the opportunity to use more of the capacity of its fuel stations and continue to reduce emissions by using LNG.

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Appendix A

Fleet Summary Statistics

Fleet Summary Statistics

Dallas Area Rapid Transit (Dallas, TX) Fleet Summary Statistics

Fleet Operations and Economics

	Diesel Control	LNG 4300	LNG 4500
Number of Vehicles	5	10	5
Period Used for Fuel and Oil Op Analysis	2/99-1/00	2/99-1/00	6/9-1/00
Total Number of Months in Period	12	12	8
Fuel and Oil Analysis Base Fleet Mileage	218,672	369,563	171,358
Period Used for Maintenance Op Analysis	6/98 - 5/99	1/99 - 1/00	7/99 - 1/00
Total Number of Months in Period	12	12	6
Maintenance Analysis Base Fleet Mileage	243,606	402,618	143,429
Average Monthly Mileage per Vehicle	4,321	3,232	4,486
Fleet Fuel Usage in Diesel #2 Equiv. Gal.	57,849	136,743	63,415
Representative Fleet MPG	3.78	1.62	1.62
Representative Fleet MPG (energy equiv)	3.78	2.70	2.70
Ratio of MPG (AF/DC)		0.71	0.71
Average Fuel Cost as Reported (with tax)	0.90 per Gal D2	0.51 per Gal LNG	0.51 per Gal LNG
Average Fuel Cost per Energy Equivalent	0.90	0.85	0.85
Fuel Cost per Mile	0.238	0.314	0.314
Number of Make-Up Oil Quarts per Mile	0.002	0.002	0.001
Oil Cost per Quart	0.65	0.85	0.85
Oil Cost per Mile	0.001	0.002	0.001
Total Scheduled Repair Cost per Mile	0.114	0.115	0.102
Total Unscheduled Repair cost per Mile	0.420	0.368	0.296
Total Maintenance Cost per Mile	0.534	0.484	0.398
Total Operating Cost per Mile	0.773	0.799	0.713

Maintenance Costs

	Diesel Control	LNG 4300	LNG 4500
Fleet Mileage	243,606	402,618	143,429
Total Parts Cost	33,807.74	54,219.93	17,228.68
Total Labor Hours	1925.6	2809.1	797.8
Average Labor Cost (@ $50.00 per hour)	96,280.00	140,454.50	39,887.50
Total Maintenance Cost	130,087.74	194,674.43	57,116.18
Total Maintenance Cost per Mile	0.534	0.484	0.398

Breakdown of Maintenance Costs by Vehicle System Similar Vehicle Lifetimes

	Diesel Control	LNG 4300	LNG 4500
Fleet Mileage	243,606	402,618	143,429
Total Engine/Fuel-Related Systems (ATA VMRS 30,31,32,33,41,42,43,44,45)			
Parts Cost	6,471.72	12,121.26	5,330.47
Labor Hours	315.8	739.7	182.6
Average Labor Cost	15,791.50	36,985.00	9,127.50
Total Cost (for system)	22,263.22	49,106.26	14,457.97
Total Cost (for system) per Mile	**0.0914**	**0.1220**	**0.1008**
Exhaust System Repairs (ATA VMRS 43)			
Parts Cost	102.44	120.38	35.87
Labor Hours	19.6	12.2	2.0
Average Labor Cost	981.00	608.50	100.00
Total Cost (for system)	1,083.44	728.88	135.87
Total Cost (for system) per Mile	**0.0044**	**0.0018**	**0.0009**
Fuel System Repairs (ATA NVMRS 44)			
Parts Cost	87.16	623.43	601.01
Labor Hours	22.3	106.3	21.6
Average Labor Cost	1,112.50	5,312.50	1.077.50
Total Cost (for system)	1,199.66	5,935.93	1,678.51
Total Cost (for system) per Mile	**0.0049**	**0.0147**	**0.0117**
Power Plant (Engine) Repairs (ATA VMRS 45)			
Parts Cost	3,375.43	4,062.19	1,406.39
Labor Hours	82.1	262.1	57.8
Average Labor Cost	4,103.50	13,107.00	2,887.50
Total Cost (for system)	7,472.93	17,169.19	4,293.89
Total Cost (for system) per Mile	**0.0307**	**0.0426**	**0.0299**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)			
Parts Cost	1,082.18	5,325.12	2,801.24
Labor Hours	134.7	254.0	88.0
Average Labor Cost	6,733.00	12,701.00	4,400.00
Total Cost (for system)	7,815.18	18,026.12	7,201.24
Total Cost (for system) per Mile	**0.0321**	**0.0448**	**0.0502**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Control	LNG 4300	LNG 4500
Air Intake System Repairs (ATA VMRS 41)			
Parts Cost	1,325.24	1,667.41	354.74
Labor Hours	22.3	24.5	5.5
Average Labor Cost	1,112.50	1,222.50	275.00
Total Cost (for system)	2,437.74	2,889.91	629.74
Total Cost (for system) per Mile	**0.0100**	**0.0072**	**0.0044**
Cooling System Repairs (ATA VMRS 42)			
Parts Cost	499.27	322.73	131.21
Labor Hours	35.0	80.7	7.8
Average Labor Cost	1,749.00	4,033.50	387.50
Total Cost (for system)	2,248.27	4,356.23	518.71
Total Cost (for system) per Mile	**0.0092**	**0.0108**	**0.0036**
Brake System Repairs (ATA VMRS 13)			
Parts Cost	1,434.07	4,077.77	1,585.65
Labor Hours	218.3	200.2	54.5
Average Labor Cost	10,915.50	10,009.00	2,725.00
Total Cost (for system)	12,349.57	14,086.77	4,310.65
Total Cost (for system) per Mile	**0.0507**	**0.0350**	**0.0301**
Transmission Repairs (ATA VMRS 27)			
Parts Cost	1,037.26	2,519.44	526.34
Labor Hours	50.0	81.0	1.5
Average Labor Cost	1,249.00	4,050.00	75.00
Total Cost (for system)	2,286.26	6,569.44	601.34
Total Cost (for system) per Mile	**0.0094**	**0.0163**	**0.0042**
Cab, Body and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)			
Parts Cost	18,216.03	26,623.77	7,949.59
Labor Hours	636.1	837.4	303.5
Average Labor Cost	31,803.50	41,872.00	15,172.50
Total Cost (for system)	50,019.53	68,495.77	23,122.09
Total Cost (for system) per Mile	**0.2053**	**0.1701**	**0.1612**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Control	LNG 4300	LNG 4500
Inspections Only – No Parts Replacements (101)			
Parts Cost	0.00	0.00	0.00
Labor Hours	347.8	564.0	184.4
Average Labor Cost	17,387.50	28,200.00	9,217.50
Total Cost (for system)	17,387.50	28,200.00	9,217.50
Total Cost (for system) per Mile	**0.0714**	**0.0700**	**0.0643**
HVAC System Repairs (ATA VMRS 01)			
Parts Cost	875.61	940.82	191.17
Labor Hours	88.4	133.8	10.7
Average Labor Cost	4,421.00	6,690.00	535.00
Total Cost (for system)	5,296.61	7,630.82	726.17
Total Cost (for system) per Mile	**0.0217**	**0.0190**	**0.0051**
Air System Repairs (ATA VMRS 10)			
Parts Cost	671.46	804.23	82.25
Labor Hours	28.8	36.5	4.0
Average Labor Cost	1,437.50	1,825.00	200.00
Total Cost (for system)	2,108.96	2,629.23	282.25
Total Cost (for system) per Mile	**0.0087**	**0.0065**	**0.0020**
Lighting System Repairs (ATA VMRS 34)			
Parts Cost	1,674.18	2,183.68	193.53
Labor Hours	132.5	137.3	25.2
Average Labor Cost	6,627.00	6,865.00	1,260.00
Total Cost (for system)	8,301.18	9,048.68	1,453.53
Total Cost (for system) per Mile	**0.0341**	**0.0225**	**0.0101**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)			
Parts Cost	3,381.82	4,131.46	1,190.47
Labor Hours	71.7	32.5	15.0
Average Labor Cost	3,586.00	1,623.50	750.00
Total Cost (for system)	6,967.82	5,754.96	1,940.47
Total Cost (for system) per Mile	**0.0286**	**0.0143**	**0.0135**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel Control	LNG 4300	LNG 4500
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft			
Parts Cost	45.59	817.50	179.21
Labor Hours	11.5	23.5	3.5
Average Labor Cost	575.00	1,172.50	175.00
Total Cost (for system)	620.59	1,990.00	354.21
Total Cost (for system) per Mile	**0.0025**	**0.0049**	**0.0025**
Tire Repairs (ATA VMRS 17)			
Parts Cost	0.00	0.00	0.00
Labor Hours	24.8	23.3	13.0
Average Labor Cost	1,237.50	1,162.50	650.00
Total Cost (for system)	1,237.50	1,162.50	650.00
Total Cost (for system) per Mile	**0.0051**	**0.0029**	**0.0045**

Notes

1. The engine and fuel-related systems were chosen to include only those systems of the vehicles that could be directly affected by the selection of an alternative fuel.

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

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

Appendix B

Emissions Test Results

Emissions Test Results

Emissions Summary–LNG Baseline Vehicles (g/mile)

Test No.	Vehicle No.	CO	NO_x	FIDHC	CH_4	NMHC	PM	CO_2	Mile/gal	BTU/mile	Miles	Odometer
3119	4324	0.25	33.2	11.8	10.8	0.05	e	2362	3.14	40948	2.02	9600
3121	4321	0.26	19.9	13.9	12.7	0.03	e	2053	3.60	35769	2.04	6900
3124	4329	0.39	12.4	16.1	14.7	0.05	e	2573	2.87	44760	2.00	10500
3127	4328	0.15	23.4	13.0	11.9	0.04	e	2286	3.24	39691	1.99	6300
3130	4320	0.29	23.6	12.2	11.1	0.03	e	2346	3.16	40691	1.99	5300
3133	4322	0.18	21.2	14.1	12.8	0.05	e	2086	3.54	36329	1.99	11400
3136	4323	0.17	10.8	15.8	14.4	0.05	e	2244	3.29	39116	1.97	9900
3139	4325	0.16	28.2	12.6	11.5	0.06	e	2099	3.52	36486	1.98	9300
3141	4326	0.20	25.9	12.6	11.4	0.07	e	2165	3.42	37602	1.98	11600
3146	4327	0.29	13.9	14.9	13.6	0.05	e	2147	3.44	37405	2.00	10700
	Average	**0.23**	**21.25**	**13.70**	**12.49**	**0.05**		**2236.10**	**3.32**	**38879.70**	**2.00**	**9150**
	St Dev	**0.08**	**7.20**	**1.51**	**1.38**	**0.01**		**160.50**	**0.23**	**2760.24**	**0.02**	**2213**
	CV %	**33%**	**34%**	**11%**	**11%**	**26%**		**7%**	**7%**	**7%**	**1%**	**24%**

Emissions Summary–Diesel Baseline Vehicles (g/mile)

Test No.	Vehicle No.	CO	NO_x	FIDHC			PM	CO_2	Mile/gal	BTU/mile	Miles	Odometer
3148	4223	3.38	26.3	1.13			0.24	2678	3.79	34327	1.99	38300
3152	4224	4.33	24.1	1.08			0.11	2620	3.87	33608	1.98	41000
3154	4222	4.92	23.0	1.25			0.41	2798	3.62	35894	1.99	17600
3157	4220	5.21	21.3	1.33			0.54	2481	4.08	31851	1.98	44300
3164	4221	4.35	32.7	1.01			0.31	2620	3.87	33599	1.98	41800
	Average	**4.44**	**25.48**	**1.16**			**0.32**	**2639.40**	**3.85**	**33855.80**	**1.98**	**36600**
	St Dev	**0.70**	**4.43**	**0.13**			**0.16**	**114.55**	**0.17**	**1459.70**	**0.01**	**10835**
	CV %	**16%**	**17%**	**11%**			**51%**	**4%**	**4%**	**4%**	**0%**	**30%**

Comparison–LNG Fueled Vehicles to Diesel Baseline Vehicles (g/mile)

Fuel Type	Test No.	CO	NO_x	FIDHC	CH_4	NMHC	PM	CO_2	Mile/gal	BTU/mile	Miles	Odometer
LNG	Average	0.234	21.25	13.70	12.49	0.05	e	2236.1	3.322	38879.7	1.996	9150
Diesel	Average	4.438	25.48	1.16		1.16	0.322	2639.4	3.846	33855.8	1.984	36600
(LNG-diesel)/diesel		-95%	-17%	1081%		-96%		-15%	-14%	15%	1%	-75%

e – too low to be detectable with a single CBD test cycle

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