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New York City Transit Hybrid and CNG Transit Buses: Interim Evaluation Results

Technical Report
NREL/TP-540-38843
January 2006

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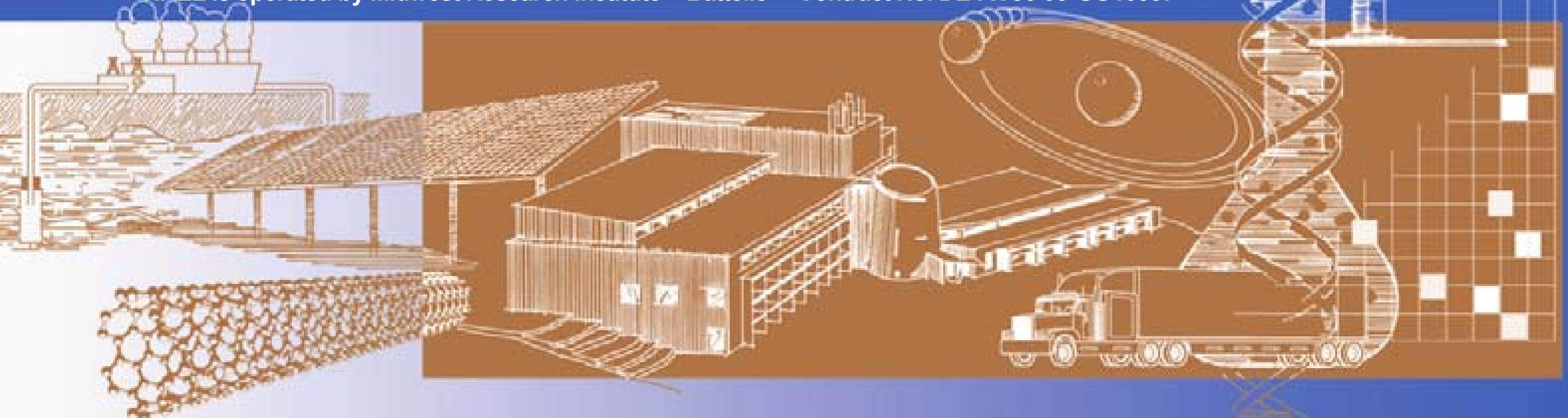

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Office of Energy Efficiency and Renewable Energy
by Midwest Research Institute • Battelle

Contract No. DE-AC36-99-GO10337

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Acknowledgements

This evaluation is funded through the Advanced Vehicle Testing Activity, which is managed by Lee Slezak, within the FreedomCAR and Vehicle Technologies Program in the U.S. Department of Energy. All publications on the NYCT hybrid bus evaluation will be posted on DOE's Energy Efficiency & Renewable Energy Website. See the Medium & Heavy Duty Vehicles section of the following link: www.eere.energy.gov/vehiclesandfuels/avta/index.shtml

This evaluation at New York City Transit (NYCT) would not have been possible without the support and cooperation of many people. The authors wish to thank each of the following:

U.S. Department of Energy
Lee Slezak

New York City Transit
Gary LaBouff
Doug Zupo
Danny Ilioiu
Glenn Maerki
Gordon Coor

BAE Systems
Tom Webb
Steve Tilyou

Orion Bus Industries
Mark Brager

Trillium USA
Jennifer de Tapia
Jan Hull

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Executive Summary

This report is part of a series of evaluations from the U.S. Department of Energy (DOE). DOE, through the National Renewable Energy Laboratory (NREL), has been tracking and evaluating new propulsion systems in transit buses and trucks for more than 10 years using an established and documented evaluation protocol. DOE/NREL evaluated the original 10 prototype diesel hybrid buses from Orion and BAE Systems (model Orion VI buses) operated at New York City Transit (NYCT). That evaluation was reported in July 2002 and provided results from the prototype buses from 1998 through 2001.

These DOE/NREL vehicle evaluations are a part of the Advanced Vehicle Testing Activity (AVTA), which supports DOE's FreedomCAR & Vehicle Technologies Program. The role of AVTA is to bridge the gap between research and development and commercial availability of advanced vehicle technologies that reduce U.S. petroleum use while improving air quality. The main objective of AVTA projects is to provide comprehensive, unbiased evaluations of advanced technologies. Data collected and analyzed include the operation, maintenance, performance, safety, cost, and emissions characteristics of advanced technology fleets and comparable conventional technology fleets operating at the same site. By comparing available advanced and conventional technology vehicles, AVTA evaluations help fleet owners and operators make informed purchasing decisions.

This report focuses on compressed natural gas (CNG) and diesel hybrid electric bus propulsion systems in NYCT's transit buses. Both of these propulsion systems are alternatives to standard diesel buses and allow for reductions in petroleum use and emissions (usually focused on reductions of particulate matter and oxides of nitrogen). CNG propulsion is an alternative to diesel fuel use, and diesel hybrid propulsion allows for increased fuel economy, which, in turn, is a reduction in petroleum use.

Evaluation Design

This report describes the evaluation results for Orion VII low floor buses at NYCT with CNG propulsion (Detroit Diesel Corporation Series 50G CNG) and hybrid propulsion (BAE Systems HybriDrive® propulsion system). These interim results represent eight out of a planned 12-month evaluation of these two groups of buses. An additional evaluation of NYCT's order of 200 Orion and BAE Systems hybrid buses will be reported separately. The evaluation period presented in this report covers October 2004 through May 2005; the final evaluation report will include data through September 2005. This interim report was created to expedite the release of information collected on these technologies.

The CNG buses evaluated were part of an order of 260 Orion VII CNG buses that started into service in September 2003 at Jackie Gleason Depot and later at West Farms Depot. NYCT expected the buses to seamlessly replace older diesel buses after CNG fueling infrastructure was added and training was completed at the newly opened West Farms Depot.

The hybrid buses evaluated were part of an order of 125 Orion VII hybrid buses with the BAE Systems series hybrid propulsion system. The buses started service in March 2004 at Mother Clara Hale Depot in Manhattan and later were also introduced at Queens Village Depot in Queens. This group of buses is the first large commercial hybrid bus delivery for Orion and BAE Systems. NYCT expected the 125 hybrid buses to seamlessly replace diesel buses after special training for high power and troubleshooting and battery conditioning activities were completed.

The CNG evaluation presented in this report includes 10 CNG Orion VII buses (model year 2002) chosen at random at West Farms Depot and nine diesel Orion V buses (model year 1994) used as a depot baseline. The baseline fleet for this evaluation is nearing the end of its useful life at NYCT (11 out of 12 years of planned use). The newer CNG buses have generally replaced the diesel buses at the depot with higher usage and lower operating costs. While comparison of newer technology to older diesel buses is not optimal, having a baseline is still valuable to fleets considering these advanced buses. In many cases, the buses being replaced are similar to those of NYCT: near or past their planned life.

The hybrid evaluation presented in this report includes 10 hybrid Orion VII buses (model year 2002) chosen at random at Mother Clara Hale Depot and nine diesel Orion V buses (model year 1999) used as a depot baseline. Although the bus model years differ by only three years, because the hybrid buses did not go into service until 2004, the diesel buses are five years older in terms of operations experience. The newer hybrid buses have generally replaced the diesel bus fleet at the depot with similar usage and much higher fuel economy and better fuel cost per mile performance.

One note of context for this evaluation: The DDC Series 50 engine is no longer available for new transit buses. Both the diesel and CNG engines are no longer available.

The evaluation presented in this report includes comparisons of CNG and hybrid Orion VII buses to older diesel buses at the two depots for bus usage, fuel economy, and miles between roadcalls (MBRC). Because of the age difference of the diesel buses and the CNG and hybrid buses (as well as warranty costs), the maintenance cost per mile comparisons are only accomplished between the CNG and hybrid Orion VII buses. The comparison of the Orion VII CNG and hybrid buses includes buses that are the same age and the same bus platform. The CNG buses at West Farms Depot and the hybrid buses at Mother Clara Hale Depot have been operated on similar duty-cycles and the maintenance practices at the two depots appear to be similar.

Implementation Experience

The implementation experience of the CNG (260 buses) and hybrid (125 buses) fleets went well, and the buses were quickly put into full service. NYCT, Orion, and BAE Systems reported that the buses are performing well from a systems perspective. West Farms Depot built a large CNG compression station that has the ability to move 6,600 scfm of natural gas and fuel buses in less than 5 minutes. Combustible gas detection was added for the maintenance area to accommodate the use of natural gas buses. The hybrid buses required that adequate space be available at the Mother Clara Hale facility for two battery conditioning stations.

The bus operators reportedly like the new buses—especially the power of the hybrid buses. Mileage accumulation for the 260 CNG buses through May 2005 was more than 9.5 million miles with a general usage rate of 2,500 monthly miles per bus. The 125 hybrid buses accumulated more than 2.6 million miles through May 2005 with a general usage rate of 2,500 monthly miles per bus. Both the CNG and hybrid bus fleets experienced miles between roadcalls (MBRC) rates above NYCT's required 4,000 MBRC (average 5,000 MBRC for CNG, 7,000 MBRC for hybrid).

Evaluation Results

The following results and discussion focus only on the selected evaluation operating depots and study bus groups.

Duty Cycle
The general duty cycle for the CNG bus evaluation location (West Farms Depot) was an average speed of 6.5 mph for 2004 and 6.3 mph for 2005. The general duty cycle for the hybrid bus evaluation location (Mother Clara Hale Depot) was an average speed of 6.5 mph and 6.1 mph for 2004 and 2005 respectively. The average speeds are comparable between the two evaluation locations. The buses at the two depots were randomly dispatched on all standard bus routes.

Bus Use
Bus use is intended as an indicator of reliability and availability for service. The lack of use may indicate downtime for maintenance or purposeful reduction of planned work for the buses. For the detailed study groups, the CNG buses had 15% higher bus use than the baseline diesel buses (CNG had 2,244 monthly miles, diesel had 1,952 monthly miles). The hybrid buses had essentially the same bus use compared to diesel at 3% higher for the hybrid buses (hybrid had 2,461 monthly miles, diesel had 2,385 monthly miles). When compared across depots, the CNG buses had a bus use similar to the hybrid buses, with the CNG buses having a 10% lower rate.

Fuel Economy
The CNG buses' average fuel economy was 25% lower than the diesel baseline buses. Average monthly fuel economy for the CNG and diesel baseline groups is shown in Figure ES-1. This fuel economy difference is typical for a low-average-speed operation for the spark-ignited natural gas engines. The hybrid buses' average fuel economy was 45% higher than the diesel baseline buses (ranging from 32% to 52% better than the diesel baseline during the evaluation period), as shown in Figure ES-2.

The diesel baseline buses for the hybrid bus evaluation have diesel engines without exhaust gas circulation (EGR). The addition of EGR for emissions control would tend to lower the diesel baseline fuel economy. The eight-month evaluation period does not include summer months, which could have reduced the hybrid bus fuel economy advantage from air conditioning loading and the ability to collect regenerative braking energy into the batteries. The summer-month fuel economy information will be provided in the final results report on this evaluation. The hybrid buses had an average fuel economy 100% higher than the CNG buses.

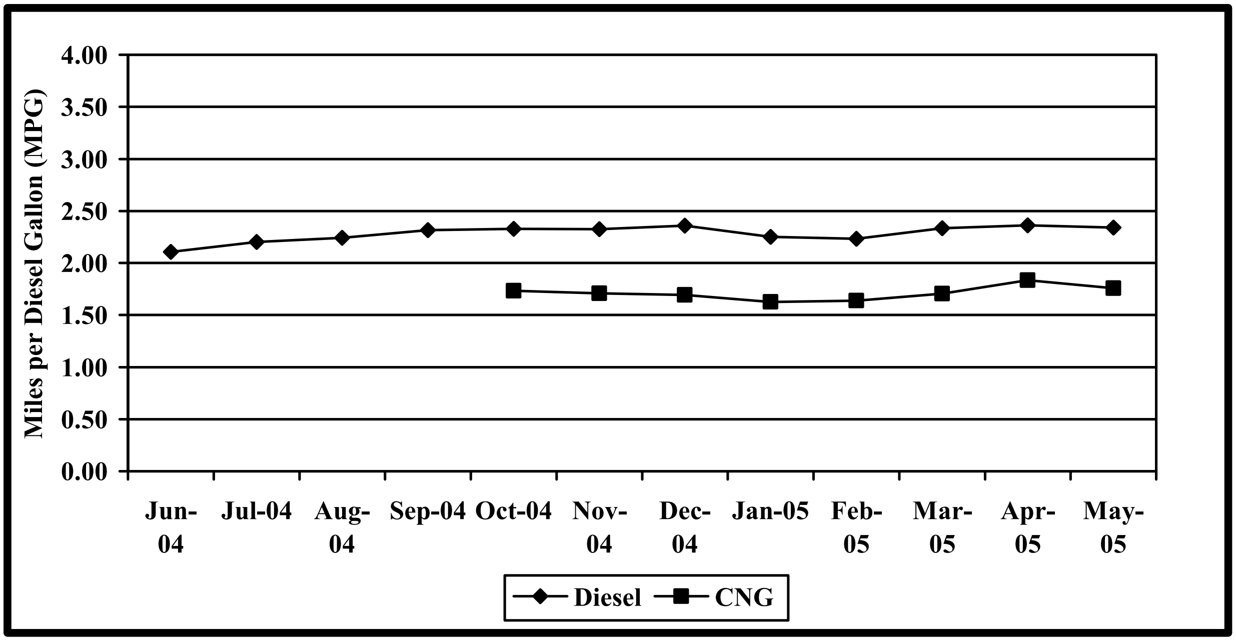


Figure ES-1. Average Fuel Economy (MPG) for CNG and Diesel at West Farms

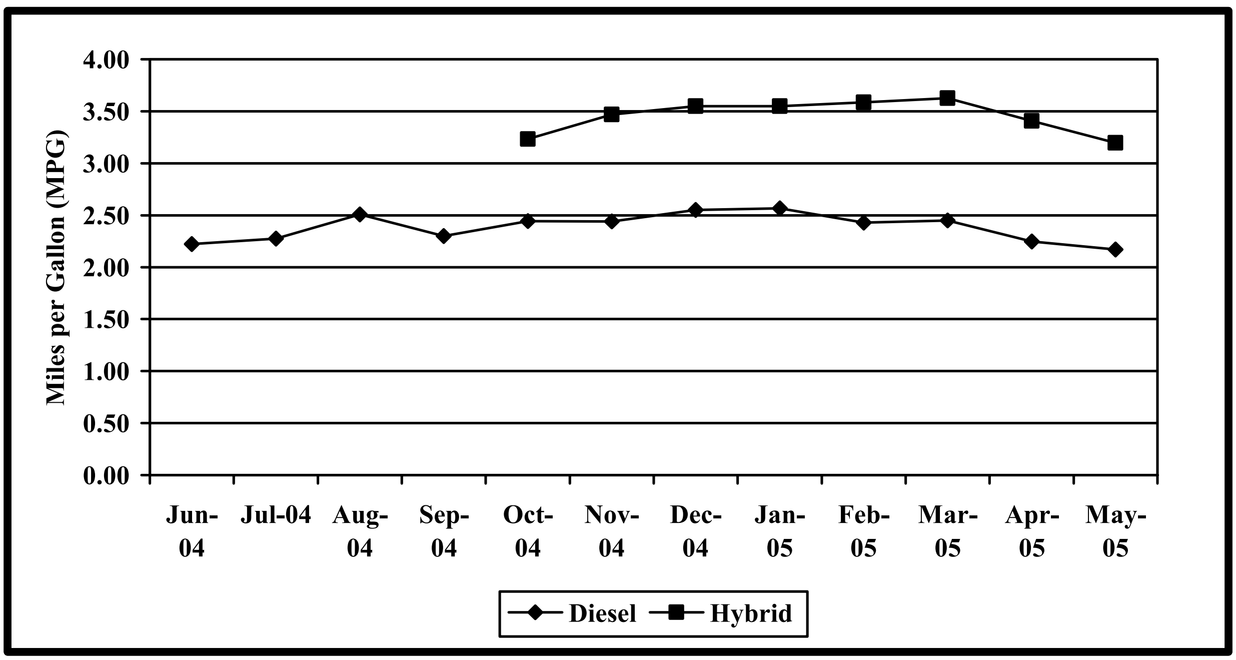


Figure ES-2. Average Fuel Economy (MPG) for Hybrid and Diesel at Mother Clara Hale

Fuel Cost

Fuel cost for the CNG buses is based on the commodity natural gas price paid by NYCT and an additional charge from Trillium USA to pay the operation and maintenance cost of the CNG fueling station. The average natural gas commodity price during the evaluation period was $0.96 per therm and the Trillium USA charge was $0.24 per therm for a total cost of $1.32 per therm or $1.78 per diesel energy equivalent gallon. The average diesel fuel cost—sulfur content less than 30 parts per million (ppm)—was $1.70 per gallon during the evaluation period. This translates into a fuel cost per mile 53% higher than the hybrid buses. The fuel cost per mile comparisons between CNG and diesel fuel may change considerably during the rest of the evaluation (June through September 2005) because of significant fuel price changes during that period.

Total Maintenance Costs

Total maintenance costs include mechanic labor at a standardized $50 per hour rate (this is not a NYCT mechanic labor rate) and parts, with no warranty costs included. The CNG buses' average total maintenance cost was 8% higher than the hybrid buses during the evaluation period.

It is early in the implementation process of the hybrid and CNG buses and the buses have had many repairs covered under warranty. Orion is in the process of completing a significant maintenance campaign for the entire Orion VII fleet at NYCT, which is planned to be completed by the end of calendar year 2005.

Propulsion-Related Maintenance Costs

Propulsion-related maintenance costs include repairs for transmission, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, exhaust, fuel, engine, and electric propulsion. The CNG buses' average propulsion-related maintenance costs were 9% lower than the hybrid buses. A summary of propulsion-related maintenance cost comparisons is shown in Table ES-3.

Table ES-3. Summary of Propulsion-Related Maintenance Cost per Mile Comparisons*

System	Hybrid vs. CNG
Total Propulsion-related	**9% (higher)**
Exhaust	111% (higher)
Fuel	-77% (lower)
Engine	-2% (lower or same)
Electric Propulsion	N/A
Non-Lighting Electrical	-58% (lower)
Air Intake	-38% (lower)
Cooling	-13% (lower)
Transmission	N/A

* The cost comparisons are provided as hybrid compared to CNG as the baseline.
((Hybrid cost per mile/CNG cost per mile) – 1) * 100% = Percent comparison
For example, the total propulsion related entry is 9% higher, this is hybrid costs being 9% higher than CNG for this category.

In this report, a roadcall (RC) is defined as an on-road failure of an in-service bus, which results in a bus being taken out of service or replaced on-route. RCs are a direct indicator of reliability for transit buses. MBRC is the typical measure for RC performance for transit buses. NYCT expects transit buses to meet or exceed a rate of 4,000 MBRC for all RCs. The CNG buses had a rate around 5,000 MBRC compared to the diesel baseline group, which had around 2,000 MBRC. The hybrid buses had a rate around 7,000 MBRC, and the diesel baseline group had around 5,000 MBRC. The diesel baseline group at West Farms is well below the NYCT expectations; the CNG buses and diesel baseline group at Mother Clara Hale Depot are both just above the NYCT expectations; the hybrid bus group is well above the NYCT expectations for MBRC.

For RCs related only to the propulsion system, the MBRC rates are lowest for the diesel baseline group at West Farms at 5,000 MBRC. The CNG buses are next at around 8,000 MBRC. At just above 10,000 MBRC, the hybrid and diesel baseline buses have similar MBRC rates for the propulsion system.

What's Next?

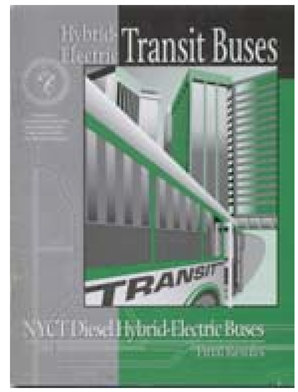
This interim evaluation report represents eight out of 12 months of evaluation planned for the CNG and hybrid buses (from the order of 125). The final results of these two study groups will be complete with data through September 2005 and should be reported in early calendar year 2006.

DOE/NREL also planned to evaluate hybrid buses from the order of 200 operating at Manhattanville Depot. Results from that evaluation will be presented separately.

NYCT has recently announced an additional order of Orion/BAE Systems hybrid buses with deliveries of 216 hybrid buses for NYCT and 284 hybrid buses for MTA Buses. The price for these hybrid buses was reported to be a little less than $500,000 each, which is reportedly about $150,000 more than a new standard clean diesel bus.

Overview

This report includes results of an evaluation of the operation of new compressed natural gas (CNG) and diesel hybrid electric buses from Orion Bus Industries (model Orion VII buses) operating at New York City Transit (NYCT). This evaluation is part of a series of evaluations from the U.S. Department of Energy (DOE). DOE, through the National Renewable Energy Laboratory (NREL), has been tracking and evaluating new propulsion systems in transit buses and trucks for more than 10 years with an established and documented evaluation protocol[1].



DOE/NREL evaluated the original 10 prototype diesel hybrid buses from Orion and BAE Systems and operated at NYCT (model Orion VI buses). Results from that evaluation[2] were published in July 2002 and provided information on the prototype buses from 1998 through 2001. NYCT worked with Orion and BAE Systems to develop, implement, and test hybrid propulsion buses in an attempt to reduce emissions and operating costs and increase fuel economy.

NYCT's Clean Bus Program was created in 1992 to lower bus fleet emissions. In 2000, NYCT established a policy of only purchasing low emission buses for new bus orders. This policy, coupled with NYCT's desire to achieve the best fuel economy, has resulted in NYCT's recent purchase order for hybrid buses. The NYCT Clean Bus Program currently includes several activities:

- Use of CNG buses
- Replacement of the oldest diesel engines (two-stroke) with newer low emissions engines (Detroit Diesel Series 50 exhaust gas recirculation engines)
- Use of ultra low sulfur diesel fuel for all diesel equipment (starting in 1998 with less than 30 parts per million (ppm) sulfur, expected to be less than 15 ppm starting in 2006)
- Addition of diesel particulate filters (DPF) to the existing and new diesel engines
- Use of hybrid propulsion buses with engines equipped with DPFs

Hybrid technology has generally been tested at NYCT in an effort to explore options other than CNG technology. This is because not all of NYCT's operating depots are cost-effective candidates for CNG infrastructure due to space constraints inside buildings and the proximity of neighboring buildings. In early 2000, NYCT ordered 260 CNG buses in two orders from Orion Bus Industries (order one was 125 buses, order two was 135 buses). At the same time, NYCT made a commitment to purchase two orders of buses with the BAE Systems hybrid propulsion system from Orion Bus Industries. One order was for 125 buses, the other for 200 buses.

[1] General Evaluation Plan, Fleet Test & Evaluation Projects, July 2002, NREL, NREL/BR-540-32392, www.nrel.gov/vehiclesandfuels/fleettest/pdfs/32392.pdf.
[2] NYCT Diesel Hybrid-Electric Buses, July 2002, NREL, NREL/BR-540-32427 www.eere.energy.gov/afdc/pdfs/nyct_diesel_hybrid_final.pdf.

Once NYCT made its commitment to purchase new CNG and hybrid buses, DOE and NREL started planning the next phase of evaluation work, which is reported here. The current DOE/NREL evaluation work is a part of DOE's Advanced Vehicle Testing Activity (AVTA). The evaluation planned with NYCT is three-fold:

- Study 10 hybrid buses from the order of 125 buses (and diesel baseline buses)
- Study 10 CNG buses from the combined order of 260 buses (and diesel baseline buses)
- Study 10 hybrid buses from the order of 200 buses (and diesel baseline buses)

This evaluation report examines early evaluation results from 10 buses from the order of 260 of CNG Orion VII buses and 10 buses from the first hybrid order of 125 hybrid buses. The DOE/NREL evaluation of the hybrid and CNG buses is two-thirds of the way through the standard 12-month evaluation. Reporting for the full 12-month evaluation will be completed in 2006. Evaluation of the order of 200 hybrid buses is also under way and will be reported in a future evaluation report.

Advanced Vehicle Testing Activity

The role of AVTA is to bridge the gap between research and development (R&D) and commercial availability of advanced vehicle technologies that reduce U.S. petroleum use while improving air quality. AVTA supports DOE's FreedomCAR & Vehicle Technologies Program in moving these technologies from R&D to market deployment by examining market factors and customer requirements, evaluating performance and durability of alternative fuel and advanced technology vehicles, and assessing the performance of these vehicles in fleet applications.

The main objective of AVTA projects is to provide comprehensive, unbiased evaluations of advanced technologies. Data collected and analyzed include the operation, maintenance, performance, safety, cost, and emissions characteristics of advanced technology fleets and comparable conventional technology fleets operating at the same site. By comparing available advanced and conventional technology vehicles, AVTA evaluations help fleet owners and operators make informed purchasing decisions.

The NREL evaluation team, which is composed of NREL and Battelle personnel, conducts AVTA medium- and heavy-duty vehicle evaluations. Hybrid electric and CNG transit buses are a few of the advanced vehicle choices available today. The evaluation team has conducted or is in the process of conducting several evaluations of advanced propulsion vehicles (Table 1). For information on other evaluations, visit www.nrel.gov/vehiclesandfuels/fleettest.

Table 1. AVTA Heavy Vehicle Evaluations

Fleet	Location	Vehicle	Technology	Evaluation Status
Norcal	San Francisco, CA	Peterbilt/378, Class 8 truck	Cummins Westport ISXG high pressure direct injection LNG and diesel	Complete and reported
IndyGo	Indianapolis, IN	Ebus 22-ft bus	Series hybrid, Capstone MicroTurbine™ (diesel)	Complete, reporting in process
Knoxville Area Transit	Knoxville, TN	Ebus 22-ft bus	Series hybrid, Capstone MicroTurbine™ (propane)	Complete, reporting in process
King County Metro	Seattle, WA	New Flyer 60-ft articulated transit bus	Parallel hybrid, GM-Allison E^P50 System™ (diesel)	In progress
New York City Transit	Manhattan, Brooklyn, Bronx, Queens, NY	Orion VII 40-ft transit bus	Series hybrid, BAE Systems HybriDrive® propulsion system (diesel), two generations; DDC S50G CNG engines	In progress and interim results reported here

Host Site Profile—NYCT

NYCT is a part of the Metropolitan Transportation Authority (MTA), which is a public-benefit corporation chartered by New York State in 1965 (www.nyct.org/index.html). In 2004, MTA had an annual operating budget of $8 billion and serviced 7.7 million passengers daily through the operation of the seven major operating divisions:

- New York City Transit (NYCT)—The largest division of MTA and the largest rail and transit bus agency in North America, NYCT serves the five boroughs (Manhattan, Bronx, Queens, Brooklyn, and Staten Island).
- Long Island Rail Road (LIRR)—The largest commuter railroad in the U.S., LIRR operates from New York City across Long Island.
- Long Island Bus (LI Bus)—LI Bus provides transit service in Long Island and connects to the LIRR and New York City.
- Metro-North Railroad—The second largest commuter railroad in the U.S., the Metro-North Railroad operates in New York City; Westchester, Putnam, Dutchess, Orange, and Rockland counties in New York and Connecticut.
- Bridges and Tunnels—This division services and maintains the bridges and tunnels, including toll collection, in the New York City area.
- Capital Construction Company—This division was formed in July 2003 to manage major capital expansion projects within the MTA.
- MTA Bus—This division was created in September 2004 to consolidate the seven bus companies operating in New York City under franchises granted by the New York City Department of Transportation.

This report focuses on the bus operations within NYCT, which operates 27 rail lines (660 track miles and 6,210 rail cars) and 244 bus routes (2,017 miles) with average weekday ridership of 7 million, or more than 2 billion passengers a year. The NYCT Department of Buses operates 4,483 buses from the following 18 operating depots in New York City.

Bronx
- West Farms
- Gun Hill
- Kingsbridge

Manhattan
- 126th Street
- Mother Clara Hale
- 100th Street
- Manhattanville
- M.J. Quill

Staten Island
- Castleton
- Yukon

Brooklyn
- Jackie Gleason
- East New York
- Flatbush
- Fresh Pond
- Ulmer Park

Queens
- Jamaica
- Queens Village
- Casey Stengel

This evaluation focuses on the West Farms depot in the Bronx and Mother Clara Hale depot in Manhattan. Other depots, including Jackie Gleason, Queens Village, Fresh Pond, and Manhattanville, were also involved in the activities described in this report.

Emissions Reductions Drive the Need for CNG and Hybrid Propulsion

The U.S. transit market, including NYCT, has been under public pressure to reduce emissions in large transit buses—especially those in urban areas. Since the early 1990s, emissions regulations have focused significant reductions of particulate matter (PM) and oxides of nitrogen (NOx) on heavy diesel engines. As shown in Table 2, transit bus applications have been specifically targeted. In the late 1990s, CNG transit bus propulsion technology emerged as the cleanest available emissions option for transit agencies. However, significant start-up costs and capital investments required to successfully operate CNG buses have kept many transit agencies looking for other options. Hybrid technology has created significant interest as that possible alternative.

Diesel bus propulsion technology has also made emissions reduction improvements and is required to become much cleaner in the next few years. PM levels have been restricted to a low level of 0.05 g/bhp-hr since 1996. This level of PM has been addressed by changes in control of engine combustion, and, in some cases, a diesel oxidation catalyst (DOC) was added.

Political pressure at local levels continues to lower fleet PM levels. Extremely low levels of PM have been achieved using a passive regenerative diesel particulate filter (DPF) in conjunction with ultra low sulfur diesel (ULSD) fuel. ULSD is defined to be diesel fuel with a sulfur content less than 15 ppm. The sulfur content of the diesel fuel must be low to keep the DPF’s catalyst working properly. Many transit agencies are using DPFs and ULSD for new buses and as retrofits to older diesel engines to minimize fleet PM levels. By the end of 2006, nearly all diesel fuel for on-road applications is required to be ULSD. The PM level is planned to be restricted for all on-road diesel vehicles to 0.01 g/bhp-hr starting in 2007, and DPF technology has been proven to reliably address this PM level[3].

Table 2. EPA Emissions Requirements for Transit Buses

Model Years	Carbon Monoxide (CO)	Hydrocarbons (HC)	NOx	PM
	g/bhp-hr	g/bhp-hr	g/bhp-hr	g/bhp-hr
1990	15.5	1.3	6.0	0.60
1991-1992	15.5	1.3	5.0	0.25
1993	15.5	1.3	5.0	0.10
1994-1995	15.5	1.3	5.0	0.07
1996-1997	15.5	1.3	5.0	0.05
1998-2003	15.5	1.3	4.0	0.05
2004-2006*	15.5	2.4 combined or 2.5 with a limit of 0.5 for non-methane hydrocarbons		0.05
2007-2010	15.5	0.14**	0.2	0.01

* The 2004 standard was moved up to 2002 as part of an agreement between the U.S. Environmental Protection Agency (EPA) and engine manufacturers.
** Non-methane hydrocarbons (NMHC)

NOx levels were reduced from 4.0 g/bhp-hr in 1998 to 2.4 g/bhp-hr combined NOx and HC in 2004 (CNG levels are 2.5 g/bhp-hr NMHC + NOx with a limit of 0.5 g/bhp-hr NMHC). The 2004 level was actually moved up to 2002 based on an agreement between EPA and diesel engine manufacturers. The emissions reduction down to 2.4 g/bhp-hr HC + NOx caused several diesel engine manufacturers to use EGR to help reduce NOx levels. The use of EGR has been reported in some locations to result in significant soot in the engine oil, caused major maintenance problems when combined with the use of DPF technology, and has been reported to have had some negative impact on fuel economy.

NOx certification levels are to be lowered to 0.2 g/bhp-hr by 2010 with a phase-in period from 2007 through 2009. During the phase in period, only half of the new engines (of a particular engine family) need to meet the 0.2 g/bhp-hr NOx level or all of the engines (of that particular family) must have NOx emissions levels less than 1.2 g/bhp-hr (or half the current standard). Most heavy diesel engine manufacturers are choosing the latter option (all engines in a family meeting the 1.2 g/bhp-hr NOx) during the phase-in period. The PM level is to be 0.01 g/bhp-hr regardless of the NOx reduction strategy. At the same time, the HC level is also being restricted down to 0.14 g/bhp-hr (or NMHC for natural gas) with a phase-in similar to NOx. For more details on this topic, see EPA's latest public report, Highway Diesel Progress Review Report 2, March 2004, EPA420-R-04-004.

For the 2010 model year and beyond, the heavy diesel engine manufacturers are exploring selective catalytic reduction (SCR) and NOx adsorber technologies to keep NOx emissions at these extremely low levels. These emissions control technologies require low sulfur levels in the diesel fuel for the catalysts to work effectively. These emissions reductions are expected to come

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[3] Emissions Reductions and Operational Experiences with Heavy-Duty Diesel Fleet Vehicles Retrofitted with Continuously Regenerated Diesel Particulate Filters in Southern California, 2001, SAE International, 2001-01-0512.

with significant fuel economy penalties that have not yet been reported. CNG propulsion has already achieved the 2007 emissions certification level for NOx at 1.2 g/bhp-hr and CNG engine manufacturers are working to meet the 2010 certification levels early. Both Cummins and Deere have reported the availability of 0.2 g/bhp-hr NOx levels in their heavy natural gas engines by 2006.

The development of diesel hybrid bus propulsion systems is exciting for people in the transit industry because the systems offer improved fuel economy during a time of fuel economy penalties for emissions control. These systems also offer the promise of a clean propulsion alternative to CNG. Many transit agencies are concerned about the cost of converting a facility to support CNG bus operations, and are therefore, much more comfortable sticking with diesel fueled vehicles.

One issue yet to be resolved for hybrid propulsion in transit is the lack of emissions reduction recognition by EPA. A hybrid propulsion system can significantly reduce the overall emissions of the vehicle simply by increasing the fuel economy. Currently, a diesel engine is certified as a stand-alone engine and not as part of a hybrid system. Therefore, there is no recognition of the emissions reduction of a hybrid propulsion system. The benefit is that the engine will be certified to the current emissions standard, and the bus will operate at a lower emissions level. The downside is that there is no way for the transit agency to get credit for the emissions reduction because of the hybrid propulsion system. The California Air Resources Board (CARB) has recognized this savings and provided hybrid bus propulsion systems with a 25% blanket reduction in emissions that can be used in the state implementation plan for emissions reductions. Currently, EPA does not recognize this benefit.

Additional benefits gained from CNG and hybrid propulsion systems in transit applications are reductions in petroleum use and increased fuel economy (for hybrid propulsion).

Project Design and Data Collection

AVTA evaluation projects focus on using a standardized process for data collection and analysis, communicating results clearly, and providing an accurate and complete evaluation. The evaluation in this report uses diesel baseline buses operating at the CNG and hybrid depots for bus usage, fuel economy, and roadcall rate comparisons, but not for maintenance costs. The much older diesel bus maintenance costs represent maintenance outside of the warranty period and both the CNG and hybrid buses have warranty costs expended by the manufacturers or NYCT during the evaluation period (as discussed later). This evaluation also uses the CNG buses as the baseline for the hybrid buses for all operations and maintenance activities.

All 40-foot buses at West Farms and Mother Clara Hale Depot were dispatched randomly on all routes. There were no restrictions on the CNG or hybrid Orion VII buses at the two depots in this evaluation report.

NYCT expects the new CNG buses to have mature diesel-like reliability and operating costs. The CNG buses do not have restrictions other than only operating from the two CNG depots. The hybrid buses were expected to be slightly less commercial than the CNG buses due to the lack of industry experience with hybrid propulsion technology. However, NYCT operated the hybrid buses with the intent that they be treated just like any other diesel bus for reliability and operations.

Data for this evaluation were taken from NYCT's data system, MIDAS. Data parameters included the following:

- Diesel fuel consumption by vehicle
- CNG fuel consumption by vehicle
- Mileage data from every vehicle
- Preventive maintenance action work orders, parts lists, labor records, and related documents
- Records of unscheduled maintenance, including roadcalls and warranty actions by vendors (when available in the data system)

The data collection was designed to cause as little disruption as possible for NYCT. Data were sent from NYCT to Battelle electronically for analysis.

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

Vehicle System Descriptions

Table 3 shows a summary of vehicle system descriptions for the CNG, hybrid, and two baseline diesel study groups of buses. The following discussion includes descriptions of each of the four study groups of buses and detailed differences between the CNG and hybrid buses versus their respective diesel baseline groups of buses.

CNG Buses at West Farms
Ten CNG buses operating at West Farms Depot were selected from the order of 260 Orion VII low floor, model year 2002, CNG buses. The CNG buses use the DDC Series 50G engine. NYCT did not select the optional catalyst for emissions aftertreatment for these buses.

Diesel Baseline Buses at West Farms
Although West Farms Depot is intended to be an all-CNG bus operating depot, some diesel buses have been operating at West Farms. The number of diesel buses operating at the depot decreased as the newer CNG buses were brought into service. The evaluation in this report used 10 Orion V high floor diesel buses as a baseline for the CNG bus evaluation of mileage usage, fuel economy, and roadcall rate results.

The diesel buses are model year 1994 and close to the end of their useful life. These diesel buses have DDC Series 50 diesel engines. One bus (number 416) had been repowered with a newer DDC Series 50 EGR engine as part of a test program. This bus was removed from the evaluation due to its significant difference in operation; however, some comments on this vehicle are provided in this evaluation.

Table 3. Vehicle System Descriptions

Vehicle System	West Farms Depot		Mother Clara Hale Depot	
	CNG Buses	Diesel Baseline	Hybrid Buses	Diesel Baseline
Number of Buses	10	9	10	9
Bus Manufacturer and Model	Orion VII, Low Floor	Orion V, High Floor	Orion VII, Low Floor	Orion V, High Floor
Model Year	2002	1994	2002	1999
Length/Width/Height	40 ft/102 in/135 in	40 ft/102 in/121 in	40 ft/102 in/132 in	40 ft/102 in/121 in
GVWR/Curb Weight	42,540/31,400 lbs	40,000/28,500 lb	42,540/31,840 lb	40,000/28,500 lb
Passenger Capacity	37 Seated, 36 Standing	39 Seated, 36 Standing	38 Seated, 32 Standing	39 Seated, 36 Standing
Engine Manufacturer and Model	DDC S50G	DDC S50	Cummins ISB (not EGR equipped)	DDC S50
Rated Horsepower	275 bhp @ 2,100 rpm	275 bhp @ 2,100 rpm	270 bhp @ 2,500 rpm	275 bhp @ 2,100 rpm
Rated Torque	900 lb-ft @ 1,200 rpm	890 lb-ft @ 1,200 rpm	660 lb-ft @ 1,600 rpm	890 lb-ft @ 1,200 rpm
Emissions Equipment	None	Retrofit DPF, Johnson Matthey	Engelhard DPX	Retrofit DPF, Johnson Matthey
Retarder/Regenerative Braking	Retarder	Retarder	Regenerative Braking	Retarder
Fuel Capacity	125 diesel equivalent gallons	125 gallons	100 gallons	125 gallons
Bus Purchase Cost*	$313,000	$290,000	$385,000	$290,000

* Costs listed in the table are actual costs at the time of purchase

CNG and Diesel Baseline Vehicle Differences

There are significant differences between the CNG and diesel baseline study groups at West Farms. The most important issue is the age difference between the fleets. This matters because the maintenance costs increase over time and significantly after five or six years of service life because of major repairs to components such as the transmission. Other differences include:

- The CNG buses are low floor and the diesel buses are high floor.
- The CNG buses have slightly higher maximum torque than the diesel buses.
- The diesel buses have a retrofitted DPF installed and the CNG buses have no exhaust aftertreatment.
- The CNG buses are heavier than the diesel buses and this slightly changed the number of maximum passengers allowed on the CNG buses versus the diesel buses.
- The CNG buses were approximately $23,000 more expensive than the diesel buses.

Hybrid Buses at Mother Clara Hale

Ten hybrid buses from the order of 125 hybrid buses were selected from the Mother Clara Hale Depot. The hybrid buses are Orion VII low floor buses and use a smaller-than-standard diesel engine (5.9 liter versus an 8.3 or 8.9 liter engine) from Cummins Engine Company. The hybrid buses are equipped with an Engelhard DPX™ for exhaust aftertreatment. This DPF is actively monitored and regenerated (as needed) as part of the BAE Systems HybriDrive hybrid propulsion system. Table 4 provides descriptions of some of the electric propulsion system.

Table 4. Hybrid Propulsion Systems

Hybrid Related Systems	Hybrid Buses
Manufacturer/Integrator	BAE Systems (HybridDrive® propulsion system)
Motor and Internal Gear Reduction	Type: AC Induction, high-power density Horsepower: 250 hp continuous (320 hp peak) Torque: 2,700 lb-ft @ 0 rpm
Generator	Type: Permanent magnet Horsepower: 160 hp continuous
Energy Storage	Type: Sealed lead acid, Hawker XT, 2 enclosures, 23 modules each, roof mounted Voltage: 520-700 VDC

Diesel Baseline Buses at Mother Clara Hale

The diesel buses at Mother Clara Hale depot are Orion V high floor buses, but from a newer bus order than those at West Farms, model year 1999. The diesel buses have DDC Series 50 diesel engines retrofitted with a DPF. These diesel buses are approaching their six to eight year rebuild and two of the ten diesel baseline buses have had the rebuild. One of those buses selected for this study (number 6014) was essentially out of service for four of the 12 month study period. This vehicle has been removed from the evaluation because of this lack of usage.

Hybrid and Diesel Baseline Vehicle Differences

The diesel buses are a few model years older than the hybrid buses. Although the hybrid buses are of model year 2002 configuration, they did not go into service until 2004. The diesel buses are high floor and the hybrid buses are low floor. The engines in the buses are also different. The hybrid buses have a Cummins ISB engine and the diesel buses have a DDC Series 50 engine. The Cummins engine is smaller and has significantly lower peak torque. The hybrid engine is intended to be rebuilt at five years of service and then replaced at eight or nine years of service. The hybrid buses have regenerative braking and a slightly smaller diesel fuel tank. The hybrid buses also cost about $95,000 more than the baseline diesel buses. The next order of hybrid buses in NYCT had a hybrid cost approximately $150,000 more than what a "new" standard diesel bus might cost.

DDC Series 50 Diesel and CNG Engine

In 2004, DDC discontinued the Series 50 diesel and CNG engine platform. For years, the diesel Series 50 engine has been the workhorse of the transit industry. DDC reported to customers that the Series 50 diesel engine platform could not meet the next round of emissions regulations and was being discontinued in preference to Mercedes Benz engines provided by DDC's parent company, DaimlerChrysler AG. With the removal of the Series 50 engine product, DDC essentially gave the U.S. transit market for 40-foot buses to Cummins and Caterpillar (and Deere Power Systems for CNG buses).

CNG Transit Bus Propulsion

Although the DDC natural gas engine was removed from the transit market, Cummins Westport Inc. and John Deere offer transit bus engine options for natural gas propulsion. Both manufacturers recently announced intentions to have standard-size, transit-bus, natural gas engines that meet the 2010 emissions certification levels available in model year 2006.

Cummins Westport is a joint venture between Cummins Engine Company and Westport Innovations. It has three main natural gas engine platforms:

- B Gas Plus (5.9 L)—Horsepower: 195, 200, 230; torque: 420, 465, 500 lb-ft
- C Gas Plus (8.3 L)—Horsepower: 250, 275, 280; torque: 660, 750, 850 lb-ft
- L Gas Plus (8.9 L)—Horsepower: 320, torque:1000 lb-ft

John Deere has one commercial natural gas engine product (6081H), which has the following settings:

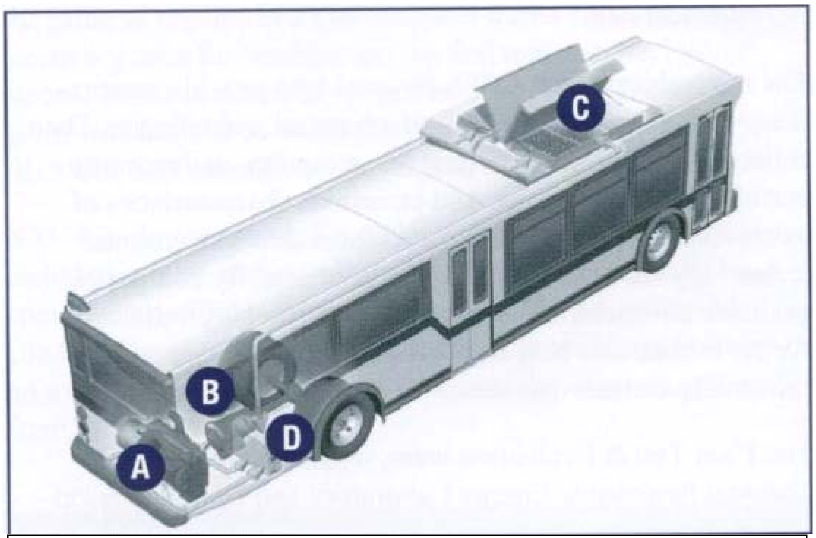
- 6081H (8.1 L)—Horsepower: 250, 275, 280; torque: 735, 800, 900 lb-ft

Both these natural gas engine manufacturers are working to make a life-cycle cost advantage for natural gas fuel use compared to equivalent diesel fuel use and diesel fuel costs.

BAE Systems HybriDrive Propulsion System

NYCT's hybrid buses are built by Orion Bus Industries (a part of DaimlerChrysler Commercial Buses North America) and use the BAE Systems HybriDrive propulsion system (Figure 1).

In this series hybrid electric system, a relatively small diesel engine running at an optimal controlled speed is connected to a generator that produces electricity for the electric drive motor and batteries. The electric motor drives the vehicle and acts as a generator to capture energy during regenerative braking. The batteries supply additional power during acceleration and hill climbing and store energy recovered during regenerative braking and idling. The battery optimization subsystem monitors and maintains the charge of each individual battery. The propulsion control subsystem manages the entire system and optimizes performance for emissions, fuel economy, and power.



A: A 5.9-liter diesel engine runs at an optimal controlled speed and is connected to a generator to produce electrical power for the drive motor and batteries.

B: The electric motor drives the vehicle and acts as a generator to capture energy during braking.

C: The batteries supply power during acceleration and hill climbing and store energy recovered during regenerative braking.

D: The propulsion control system manages the entire system and optimizes performance for emissions, fuel economy, and power.

Figure 1. BAE Systems HybriDrive Propulsion System

NYCT Facilities

NYCT has two CNG operating depots—Jackie Gleason Depot in Brooklyn and West Farms Depot in the Bronx. The newly built West Farms CNG depot, shown in Figure 2, opened on September 7, 2003. An older depot, Coliseum Depot, was originally located where West Farms is now. West Farms has 157,000 square feet of office and maintenance space, outdoor parking for buses, and operates 256 buses including 163 CNG buses.

CNG fueling is provided under contract from Trillium USA and is integrated into the fueling island as shown in Figure 3. The CNG compressor station is outside the building (Figure 4) and includes three 800-horsepower compressors with a total output of 6,600 scfm. The capital cost for the facility was \$7.4 million including \$2 million for construction costs to blast through solid rock to install the underground natural gas lines. The current cost for compression and upkeep for the CNG station is \$0.24 per therm or \$0.32 per diesel equivalent gallon (in addition to the base natural gas commodity price).

Figure 2. West Farms Depot

Figure 3. CNG Fuel Lanes at West Farms Depot

Figure 4. CNG Compression Station at West Farms Depot

The order of 125 hybrid buses was split between two operating depots—Mother Clara Hale Depot and Queens Village Depot. The Mother Clara Hale Depot, shown in Figure 5, has 125,690 square feet of office and maintenance space, indoor parking for buses, and operates 125 buses including 62 hybrids. Every six months, the hybrid buses require a conditioning charge process for the traction batteries (which takes as much as 24 hours) as part of their scheduled maintenance routine. The conditioning is done to help extend the battery pack life to at least three years. The conditioning charger is shown in Figure 6. The cost of each charger unit is $70,000. The depots with the Orion/BAE System hybrid propulsion system are planned to receive at least two of the conditioner units.


Figure 5. Mother Clara Hale Depot

Figure 6. Hybrid Traction Battery Conditioning Unit

Implementation Experience

The discussion in this section is based on overall fleet level results of mileage accumulation and roadcalls (RCs) for the CNG and hybrid bus fleets—260 CNG buses and 125 hybrid buses. NYCT has treated both of these fleets as standard buses for service. The depots have not been given special treatment for meeting pullout requirements for service.

For each study group (CNG and hybrid), several topics are covered. They include:

- Background on NYCT expectations
- Bus delivery
- Total mileage accumulation from March 2003 through May 2005 for CNG and March 2004 through May 2005 for hybrid
- Average monthly mileage per bus
- Miles between roadcalls (MBRC) for all RCs and for propulsion-related only
- Fleet issues and warranty maintenance campaigns

NYCT has three standard expectations and measures for transit bus operations. They are availability, reliability, and recovery time.

- Availability—This measure, which should be 85% or above, allows for scheduled and some unscheduled maintenance for the bus. Buses that fall below the 85% availability can cause problems with having enough buses to make service.
- Reliability—The measure should be above 4,000 MBRC for all RCs.
- Recovery time—Buses should not be out of service for more than three days for any maintenance action (or anything else).

Of these three topics, reliability (MBRC) is the only one covered in this report. Availability and recovery time were not available for this study, but are implied in bus usage levels.

CNG Buses

NYCT has 481 CNG buses split between the West Farms and Jackie Gleason depots. The addition of significantly more CNG buses would require another depot to be converted to CNG fueling and maintenance operations. The cost of this conversion was estimated to be higher than NYCT is willing to pay as long as diesel hybrid buses are a viable option in purchase and operations costs.

NYCT was an early adopter of CNG transit buses. In 1995, it purchased 34 CNG buses; this number grew to 221 by 2001. These CNG buses were operating at Jackie Gleason Depot. As mentioned earlier, NYCT purchased 260 new CNG Orion VII buses. There were some delays in delivery of these buses due to Orion's delays in meeting NYCT's rigorous structural qualification requirements.

The 260 CNG Orion VII buses were delivered and placed into service from March 2003 through approximately November 2004. Jackie Gleason Depot started its first new CNG bus in service in March 2003; West Farms Depot started its first new CNG bus in service in September 2003. Figure 7 shows total mileage accumulation at the two CNG bus depots. At the end of May 2005, the total Orion VII CNG fleet had reached 9.5 million miles of operation. Figure 8 shows average monthly mileage per CNG bus at the two CNG depots. This figure shows that the CNG buses were placed into service quickly and met an average usage per month of 2,300 to 2,500 miles per month.

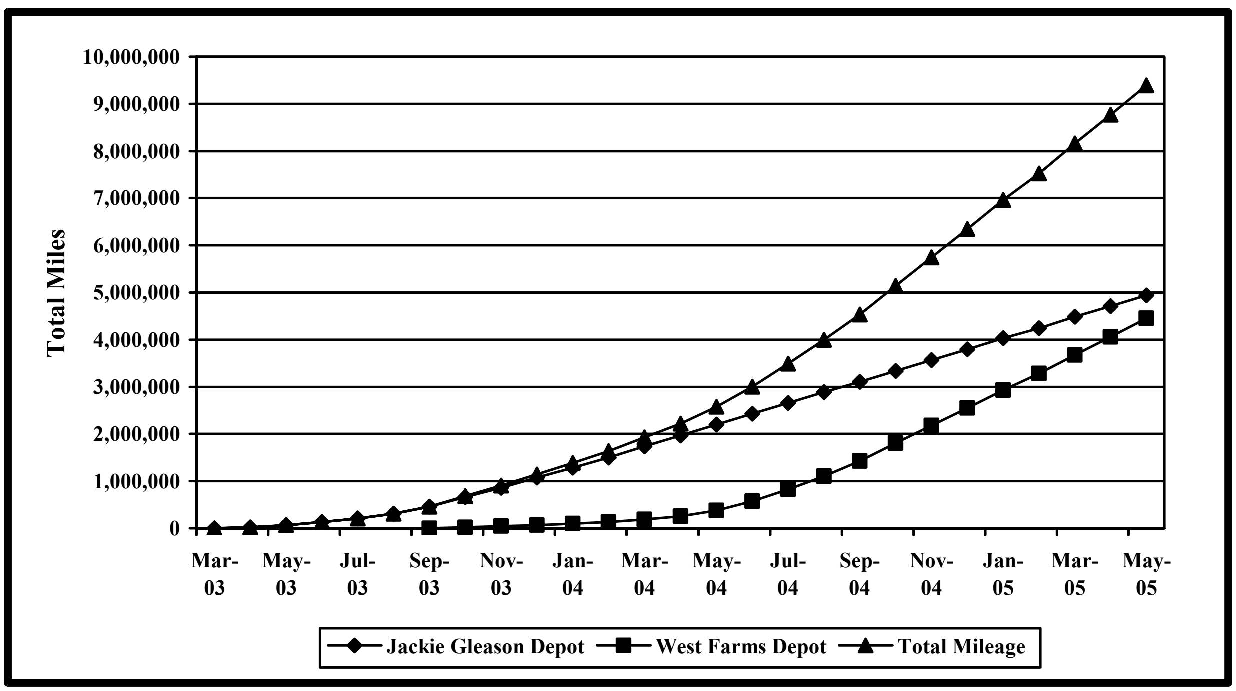


Figure 7. CNG Bus Fleet Cumulative Mileage

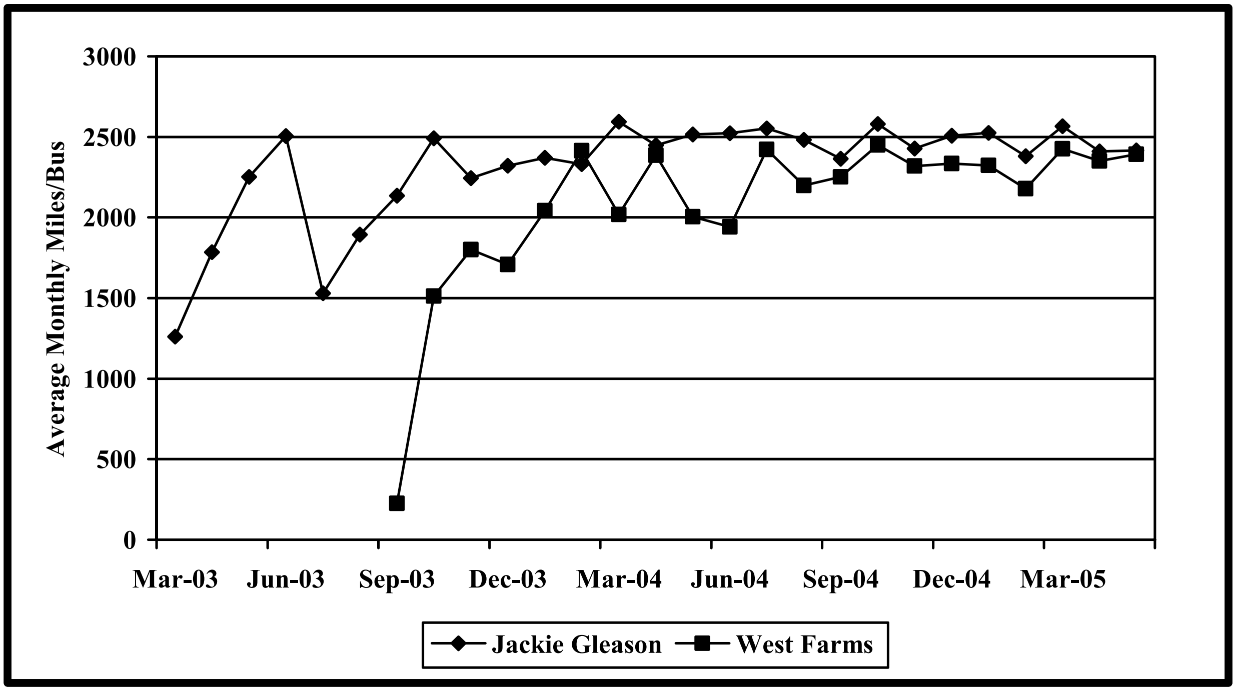


Figure 8. CNG Bus Fleet Cumulative Average Monthly Mileage per Bus

Figure 9 shows MBRC for CNG buses at both CNG bus depots. The figure shows that for all RCs, the Gleason Depot CNG buses were at or above 4,000 MBRC (as expected/required by NYCT) by April 2004; West Farms achieved this in December 2004. The propulsion-related MBRC for both depots settled around 7,000 MBRC. The most common RCs for the propulsion system were related to the engine, no start, electrical shutdown, or problem indicator lights.

General problems at start-up or within the first year or so of operation were mostly related to the Orion VII bus, rather than the propulsion system, such as axle bolts coming loose and cooling pump failures. Items specific to the CNG bus fleet included:

- CNG engines were burning excessive amounts of oil—determined to be an engineering and design issue; cylinder kits and sleeves in the process of being changed out
- Spark plugs were initially a reliability issue (5,000 miles between changes)—changed to a different spark plug; now getting the required 24,000 miles between changes
- Fuel door switches; being changed out
- Hydraulic cooling fan motor; changing configuration and motors
- Had regulator problems; now resolved

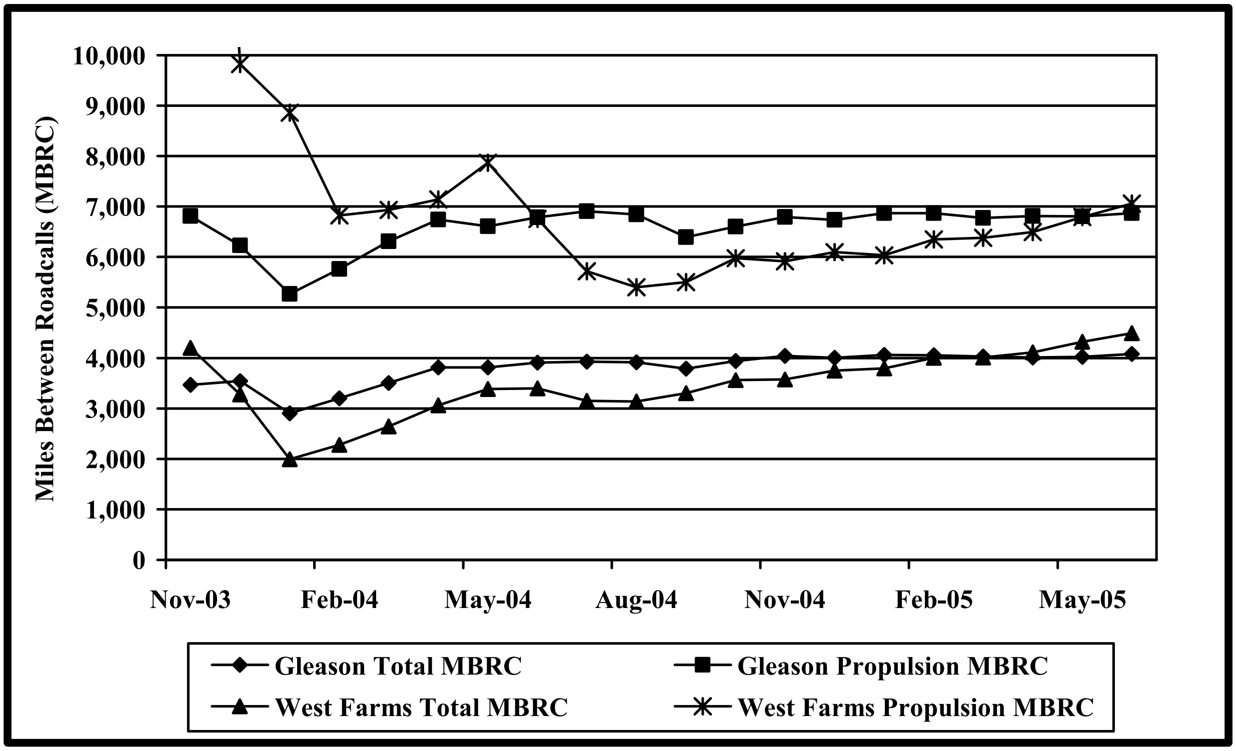


Figure 9. CNG Bus Fleet Cumulative Average MBRC

Hybrid Buses
NYCT started operating prototype diesel hybrid buses from Orion and BAE Systems in 1998 with the first of 10 prototype buses. This prototype operation led to a large purchase of hybrid buses to solidify commitment from NYCT and the manufacturers (Orion and BAE Systems). The new orders of 125 hybrid buses and 200 hybrid buses have now been delivered to NYCT. The order of 125 hybrid buses has been split between two NYCT operating depots—Mother Clara Hale and Queens Village. The order of 200 hybrid buses has been split between another two NYCT operating depots—Fresh Pond and Manhattanville (operating location for the original 10 prototype hybrid buses).

The delivery of the hybrid buses was delayed due to the acceptance of the CNG bus order (mostly for issues with NYCT purchasing a new platform vehicle, the Orion VII). The hybrid bus order of 125 buses was placed into service from March 2004 through December 2004. The first new hybrid bus was placed into service at Mother Clara Hale Depot in March 2004 and the first new hybrid bus was placed into service at Queens Village Depot in November 2004.

Figure 10 shows total mileage accumulation at these two hybrid bus depots and a total. At the end of May 2005, the hybrid fleet had reached 2.6 million miles of operation. Figure 11 shows average monthly mileage per hybrid bus at the two hybrid depots. This figure shows that the hybrid buses were placed into service quickly and came up to the average usage of 2,400 miles per month for Mother Clara Hale and approximately 3,000 miles per month for Queens Village.

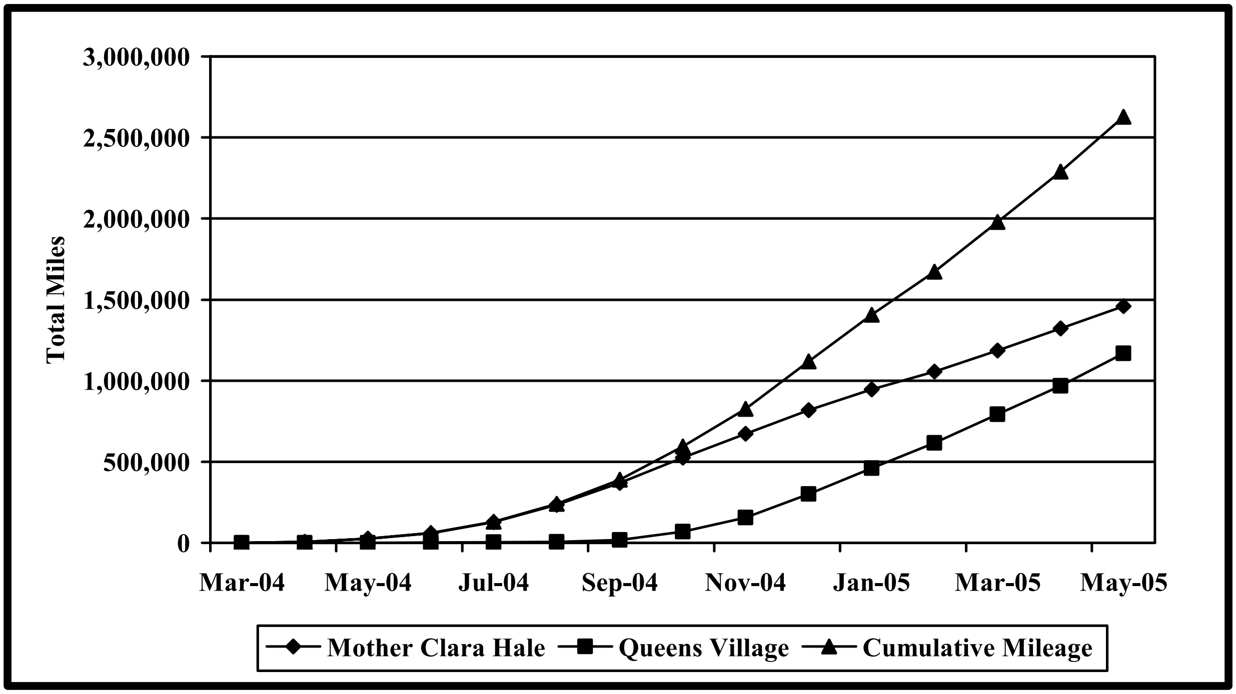


Figure 10. Hybrid Fleet Cumulative Mileage

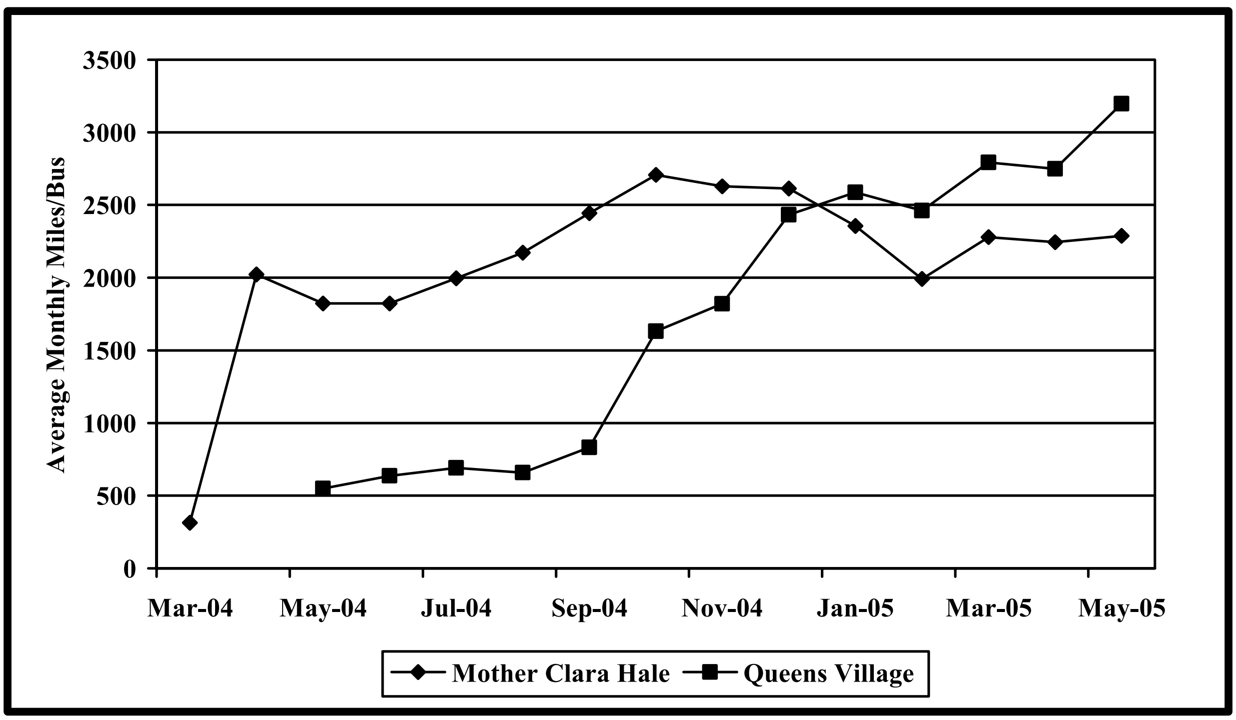


Figure 11. Hybrid Fleet Cumulative Average Monthly Mileage per Bus

Figure 12 shows MBRC for hybrid buses at the two hybrid bus depots. The figure shows that for all RCs, the Mother Clara Hale depot hybrid buses were at or above 4,000 MBRC (as expected/required by NYCT) by October 2004; the buses at Queens Village achieved this in December 2004. The propulsion-related MBRC for Mother Clara Hale is above 6,000 and

Queens Village is approaching an MBRC of 10,000. The propulsion-related MBRC for both depots jumped in December 2004 (this is not as noticeable for Mother Clara Hale because of the longer data period prior to the change). The most common RCs for the propulsion system were related to the engine and the hybrid control system shutdown or problem indicator lights. Many of the shutdown indicators for the hybrid propulsion system did not necessarily mean there was a repair required for the propulsion system. Problems in other systems can also be indicated by the propulsion control system.

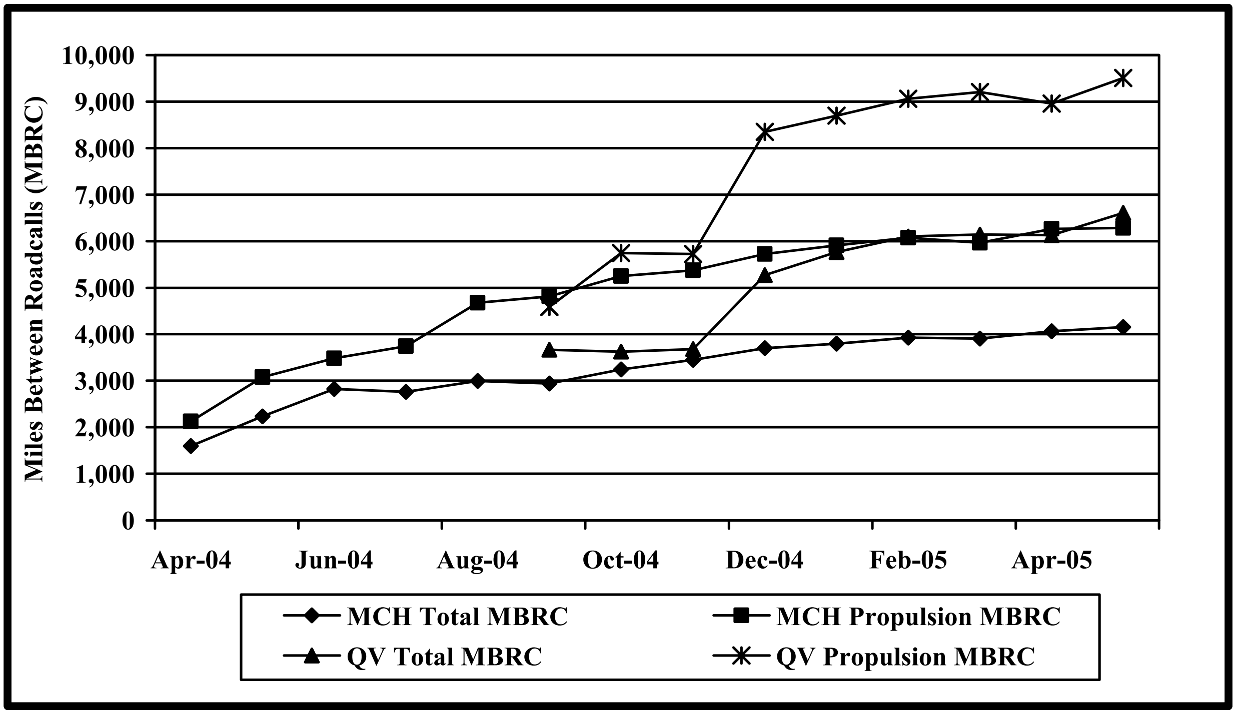


Figure 12. Hybrid Fleet Cumulative Average MBRC

Specific maintenance items that have been worked on the hybrid buses have been:

- Radiator baffle—surge tank overflowing
- Water in wiring/connectors
- Engine grid heater relay
- Water in engine from air intake
- Issues with the triple pump
- Power control system (PCS) internal coolant leaks; some modification to the cooling system was done.
- Software upgrades; moved some of the propulsion fault codes from the dash display to be on the engine compartment display; changed signal processing to be more tolerant of wiring intermittent signals.

The entire Orion VII fleet (CNG and hybrid) is currently undergoing a warranty maintenance campaign to address the items listed above for both groups. This is a significant fleet campaign that is planned to be completed by the end of 2005.

Evaluation Results

In any evaluation, a starting point must be chosen. In the DOE/NREL evaluations, this starting point is typically called a "clean point." The clean point is chosen to avoid some of the early and expected operations problems with a new vehicle going into service, such as early warranty maintenance campaigns. In some cases, the clean point may require three to six months of operation before the evaluation can start.

October 1, 2004 has been used as the start date for the evaluation at West Farms and Mother Clara Hale depots; however, this is not a clean point. As mentioned earlier, Orion has agreed to a significant campaign of the entire Orion VII fleet at NYCT (hybrid and CNG) to be completed at the end of 2005. The entire evaluation of the hybrid order of 125 and the CNG buses will be complete before that major campaign will be complete. The results and impact of this campaign is intended to be captured during the evaluation of the order of 200 hybrid buses.

This report provides results from an eight-month evaluation period for the CNG and hybrid buses that ended in May 2005. The evaluation of the CNG and first order of hybrid buses will be complete when data through September 30, 2005, is collected, evaluated, and published in a later report. The start date was chosen to remove a fueling data collection problem at the fueling stations at both depots during the summer of 2004. The two study groups of older diesel baseline buses were evaluated during a 12-month period of June 1, 2004 to May 31, 2005. The diesel buses were being transferred out of the two study depots due to the addition of the new CNG and hybrid buses, so the evaluation period of the diesel baselines was selected to start a little earlier than the two study bus groups (CNG and hybrid).

Route Descriptions

West Farms Depot operates 40-foot buses on 11 to 13 Bronx routes. Buses at West Farms are randomly dispatched on all routes, and there are no route assignment restrictions for the CNG buses. As shown in Table 5, bus operations from West Farms for 40-foot standard buses had an overall average speed of 6.47 mph in 2004 and 6.33 mph in 2005.

Table 5. Average Speed for All Standard Buses (40-foot) at West Farms

Year	Day of Week	Miles/Day	Hours	Avg. Speed
2004	Weekday	18,825.29	2,939.1	6.41
	Saturday	15,416.50	2,359.2	6.53
	Sunday	12,947.86	1,869.3	6.93
	Total	**122,490.81**	**18,923.7**	**6.47**
2005	Weekday	18,522.74	2,962.4	6.25
	Saturday	14,902.57	2,319.1	6.43
	Sunday	12,499.17	1,832.2	6.82
	Total	**120,015.44**	**18,963.3**	**6.33**

Mother Clara Hale Depot operates 40-foot buses on two Bronx routes and five Manhattan Routes. Buses at the depot are randomly dispatched on all routes, and there are no route assignment restrictions for the hybrid buses. As shown in Table 6, bus operations from Mother Clara Hale Depot for 40-foot standard buses had an overall average speed of 6.52 mph in 2004 and 6.13 mph in 2005 (this reduction in average speed was the result of a high-speed route being moved to another depot).

Both depots showed a general downward trend in average speed from 2004 to 2005. Much of these decreases in average speed are likely caused by an increase in congestion on the routes and some changes in NYCT's bus scheduling. Average speeds for the West Farms and Mother Clara Hale depots appear to be similar and comparable. Total mileage differences are caused by the number of buses assigned to the depots (250 buses at West Farms and 125 buses at Mother Clara Hale).

Table 6. Average Speed for All Standard Buses (40-foot) at Mother Clara Hale

Year	Day of Week	Miles/Day	Hours	Avg. Speed
2004	Weekday	9,722.27	1,542.4	6.30
	Saturday	8,329.96	1,180.1	7.06
	Sunday	7,201.13	951.8	7.57
	Total	**64,142.44**	**9,843.9**	**6.52**
2005	Weekday	8,472.37	1,418.1	5.97
	Saturday	6,760.61	1,031.0	6.56
	Sunday	5,501.83	790.2	6.96
	Total	**54,624.29**	**8,911.7**	**6.13**

Bus Use

Bus use is intended as an indicator of reliability and availability for bus service. The lack of bus usage may be an indication of downtime for maintenance or purposeful reduction of planned work for the buses.

Table 7 shows average monthly mileage per bus for the evaluation period for the diesel and CNG buses at West Farms. Figure 13 shows cumulative average monthly miles per bus. The CNG buses had an average of 2,244 miles per bus and the diesel buses had an average of 1,952 miles per bus. The evaluation period for the CNG buses was eight months; the diesel bus evaluation period was 12 months. However, most of the diesel buses have fewer than 12 months used because of in-chassis rebuilds of the engines. The usage of the CNG buses was significantly higher (overall 15% higher) than the diesel buses during most of the evaluation period. This occurred because of the age of the diesel buses and the cost of operation. NYCT tends to operate the more cost effective buses, which are typically the newer ones.

Table 8 shows average monthly mileage per bus for the diesel and hybrid buses at Mother Clara Hale Depot. Figure 14 shows the average monthly miles per bus for the hybrid and diesel buses. The hybrid buses showed an average of 2,461 miles per bus; the diesel buses had an average of 2,385 miles per bus. By the end of the evaluation period shown, these two fleets were being used at essentially the same rate.

The CNG and hybrid buses also have similar usage rates with the hybrid bus usage about 10% higher than the CNG buses.

Table 7. Monthly Mileage per Bus at West Farms

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average
403	228,750	247,081	18,331	10	1,833
407	227,496	248,486	20,990	11	1,908
408	211,730	233,021	21,291	11	1,936
412	228,689	247,729	19,040	10	1,904
413	223,767	242,570	18,803	10	1,880
428	204,180	226,368	22,188	11	2,017
438	218,618	240,833	22,215	11	2,020
448	222,992	247,696	24,704	12	2,059
450	227,366	251,068	23,702	12	1,975
Diesel			**191,264**	**98**	**1,952**
7657	26,249	44,957	18,708	8	2,339
7662	20,490	39,909	19,419	8	2,427
7666	23,754	36,841	13,087	8	1,636
7670	25,240	43,178	17,938	8	2,242
7677	16,597	34,590	17,993	8	2,249
7688	13,231	31,747	18,516	8	2,315
7708	9,772	29,116	19,344	8	2,418
7715	11,386	29,699	18,313	8	2,289
7719	10,412	27,895	17,483	8	2,185
7721	8,454	27,200	18,746	8	2,343
CNG			**179,547**	**80**	**2,244**

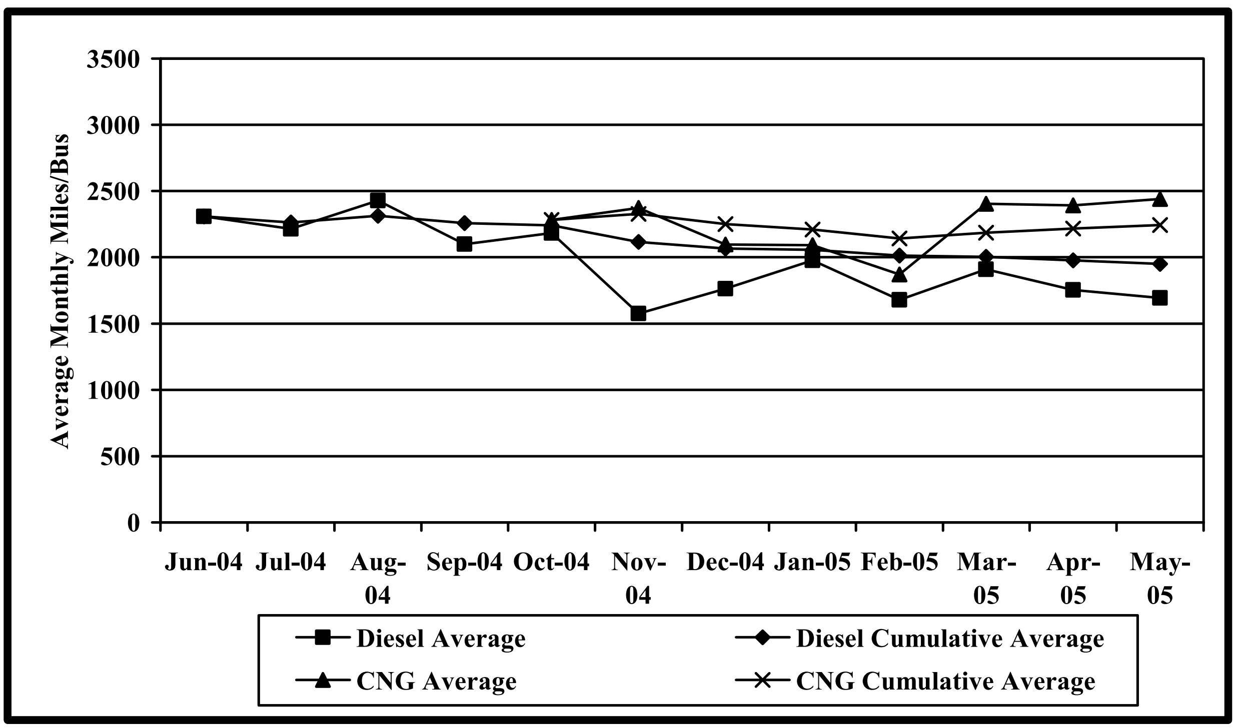


Figure 13. Monthly Mileage per Bus at West Farms Depot

Table 8. Monthly Mileage per Bus at Mother Clara Hale Depot

Bus	Starting Hubodometer	Ending Hubodometer	Total Mileage	Months	Monthly Average
6002	143,605	172,184	28,579	12	2,382
6004	156,587	185,787	29,200	12	2,433
6005	163,153	193,499	30,346	12	2,529
6006	160,513	189,600	29,087	12	2,424
6008	163,845	193,285	29,440	12	2,453
6011	156,097	183,498	27,401	12	2,283
6015	159,521	186,976	27,455	12	2,288
6018	162,137	191,639	29,502	12	2,459
6020	161,862	188,476	26,614	12	2,218
Diesel			**257,624**	**108**	**2,385**
6367	15,224	32,036	16,812	8	2,102
6368	16,391	33,856	18,465	8	2,308
6369	14,081	32,626	18,545	8	2,318
6375	12,063	33,315	21,252	8	2,657
6378	11,328	31,862	20,534	8	2,567
6379	8,874	29,327	20,453	8	2,557
6380	13,320	30,283	16,963	7	2,423
6381	10,904	30,374	19,470	8	2,434
6382	12,889	33,932	21,043	8	2,630
6387	11,260	32,118	20,858	8	2,607
Hybrid			**194,395**	**79**	**2,461**

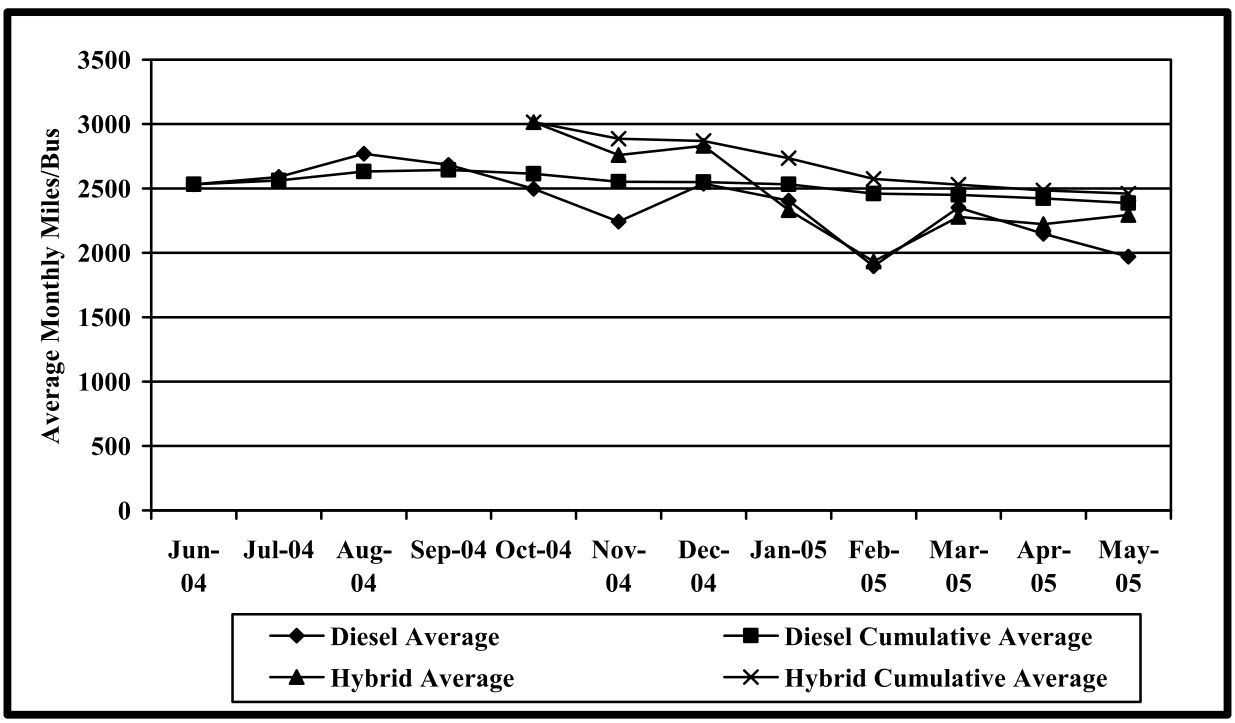


Figure 14. Monthly Mileage at Mother Clara Hale Depot

Fuel Economy and Cost

NYCT buses use Jet A diesel fuel, which is designated as aircraft fuel. NYCT and other transit bus operators in the area use Jet A diesel fuel because of its availability in the city. This fuel designation is slightly higher grade than diesel #1. As mentioned earlier, NYCT is using ultra low sulfur diesel fuel at less than 30 ppm sulfur content for its Jet A diesel fuel. This sulfur level is expected to be less than 15 ppm by 2006.

CNG fuel is provided at West Farms by a compression station operated and serviced by Trillium USA. The CNG study fleet fuel consumption and economy is shown in Table 9 and Figure 15. The fuel economy for the CNG buses is shown in diesel gallon equivalent units based on an energy conversion of CNG to diesel. The CNG study group has a 25% lower fuel economy than the non-EGR diesel buses. Based on the duty cycle at West Farms (average speed between 6.3 mph and 6.5 mph), this lower fuel economy is within typical expectations based on previous studies[4]. The low average speed of the operation is the key to this significantly lower fuel economy. Figure 15 shows the difference between the CNG and diesel study group fuel economy is staying generally the same over time.

The one diesel bus that was removed from the evaluation (bus 416) is listed in the table with a fuel economy of 2.04 mpg. This bus had a new DDC Series 50 EGR engine installed in place of the original DDC Series 50 engine instead of an in-chassis rebuild. This vehicle showed a fuel economy that was consistently 10% lower than the rest of the diesel baseline study group at West Farms Depot.

The hybrid study fleet fuel consumption and economy is shown in Table 10 and Figure 16. The fuel economy for the hybrid buses is 45% higher than the non-EGR diesel buses. This higher fuel economy for the hybrid buses is expected; however, the data period is only eight months. The last four months of the 12-month evaluation period are summer operation in New York, which requires significant load for air conditioning, and the heat may inhibit brake regeneration at times. As shown for the CNG and diesel baseline groups, the hybrid buses and the baseline diesel group have similarly shaped fuel economy curves. The hybrid bus fuel economy has fluctuated between 32% and 52% higher than for the diesel buses in the same time frame at Mother Clara Hale Depot.

Using this data between the two study depots, the hybrid buses have fluctuated between 80% and 120% higher fuel economy than the CNG buses based on diesel equivalent units.

During the evaluation period, diesel fuel at NYCT was an average of $1.70 per gallon for ultra low sulfur diesel fuel with sulfur less than 30 ppm. The diesel fuel cost has gone up significantly since the end of the evaluation period for this report (currently $2.26 per gallon in September 2005). This difference in average diesel fuel cost will be accounted for in the final results report for this evaluation at NYCT.

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[4] For example, DART's LNG Bus Fleet, Final Results, 2000, NREL, NREL/BR-540-28739 (www.nrel.gov/vehiclesandfuels/fleettest/pdfs/28739.pdf) and Alternative Fuel Transit Buses, Final Results,", 1996, NREL, NREL/TP-425-20513 (www.eere.energy.gov/afdc/pdfs/transbus.pdf)

Table 9. Fuel Use and Economy at West Farms

Bus	Mileage (Fuel Base)	Gallons Consumed	MPG
403	17,762	7,916.7	2.24
407	20,542	8,862.5	2.32
408	21,064	9,195.2	2.29
412	18,475	8,200.4	2.25
413	18,473	8,106.6	2.28
416*	20,488	10,053.7	2.04
428	21,774	9,744.9	2.23
438	21,310	9,124.7	2.34
448	24,269	10,647.1	2.28
450	23,013	10,221.3	2.25
Diesel	**186,682**	**82,019.4**	**2.28**
7657	16,461	9,559.6	1.72
7662	17,793	9,505.9	1.87
7666	12,320	7,189.5	1.71
7670	15,641	9,249.2	1.69
7677	15,832	9,132.7	1.73
7688	16,683	9,993.6	1.67
7708	18,029	11,016.5	1.64
7715	17,547	10,099.2	1.74
7719	16,470	10,315.6	1.60
7721	16,987	9,588.3	1.77
CNG	**163,763**	**95,650.1**	**1.71**

* Results for bus 416 are not included in the total.

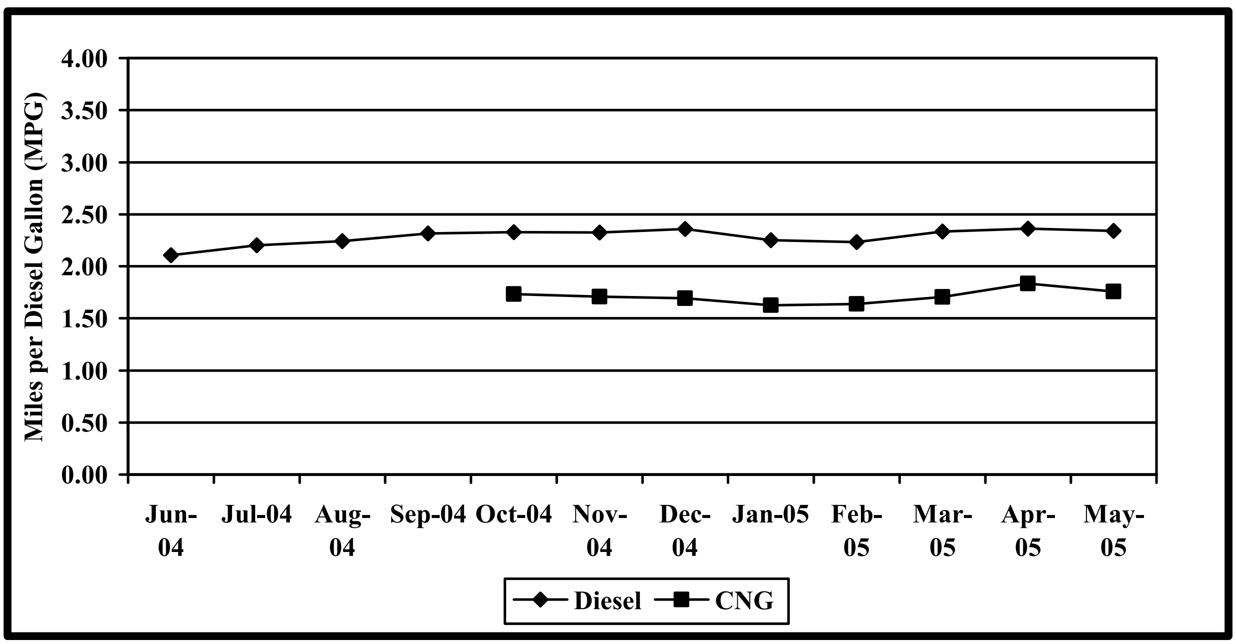

Figure 15. Average Fuel Economy (MPG) for CNG and Diesel Buses at West Farms Depot

Table 10. Fuel Use and Economy at Mother Clara Hale

Bus	Mileage (Fuel Base)	Gallons Consumed	MPG
6002	27,467	11,805.5	2.33
6004	28,859	11,936.0	2.42
6005	28,742	11,704.5	2.46
6006	27,978	12,021.5	2.33
6008	28,754	11,929.0	2.41
6011	26,614	11,401.0	2.33
6015	27,078	11,614.0	2.33
6018	29,048	11,909.5	2.44
6020	25,450	10,816.5	2.35
Diesel	**249,990**	**105,137.5**	**2.38**
6367	15,707	4,507.5	3.48
6368	15,545	4,658.0	3.34
6369	16,611	4,703.0	3.53
6375	14,057	4,021.5	3.50
6378	17,811	5,041.0	3.53
6379	18,464	5,427.5	3.40
6380	13,782	4,334.0	3.18
6381	17,843	5,060.4	3.53
6382	19,100	5,504.5	3.47
6387	19,107	5,591.5	3.42
Hybrid	**168,027**	**48,848.9**	**3.44**

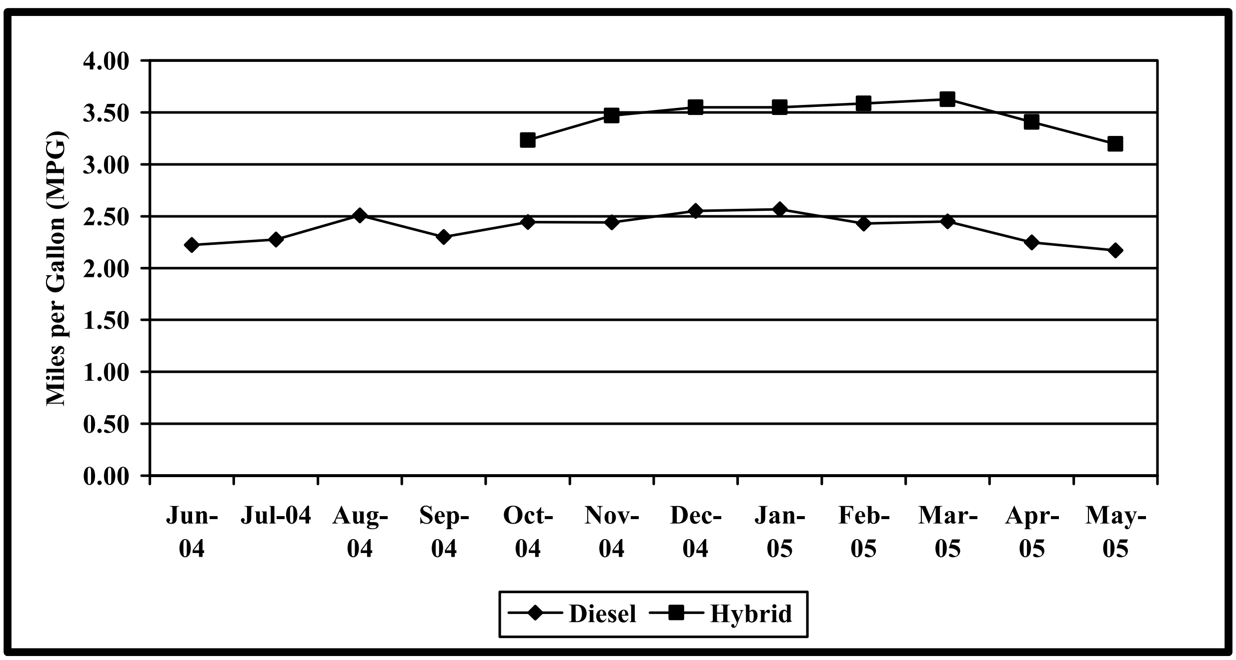

Figure 16. Average Fuel Economy (MPG) for Hybrid and Diesel Buses at Mother Clara Hale Depot

NYCT's CNG cost is based on two components—the commodity price of the natural gas from the pipeline and the Trillium add-on to pay for the station operation. Over the evaluation period, this has been $0.96 per therm for the natural gas and $0.24 per therm for Trillium, which results in a total cost of $1.32 per therm or $1.78 per diesel equivalent gallon.

When compared to the diesel baseline study group, the fuel cost per mile for the CNG buses was $1.04 per mile for CNG and $0.75 per mile for diesel—39% higher for CNG at West Farms Depot. The hybrid buses were 31% lower than their diesel baseline study group at $0.72 per mile for diesel and $0.49 per mile for hybrid buses at Mother Clara Hale Depot. Across the depots, the CNG buses have a fuel cost per mile 53% higher than the hybrid buses.

Maintenance Analysis

The maintenance analysis in this section only includes the CNG and hybrid buses. The diesel baseline buses at the two depots are much older and have much higher maintenance costs. The CNG and hybrid buses are new enough that they have much of the expensive maintenance done under warranty by the manufacturers and their distributor mechanics. When possible, this warranty maintenance cost is captured and provided in the report, but is not included in the maintenance cost analysis. All of the comparisons in this section are hybrid buses compared to CNG buses as the baseline.

Both the CNG and hybrid buses are similar in age and the maintenance costs have been collected in a similar way for each study group. The duty cycle and maintenance practices at West Farms and Mother Clara Hale depots are similar and do allow a comparison between the CNG and hybrid buses. These buses are the same model (Orion VII) and have been in service about the same amount of time.

For the CNG and hybrid buses, maintenance data were collected from the start of operations. All work orders and parts information available were collected for the study buses. The maintenance analysis discussions include only maintenance data from the evaluation period of October 2004 through May 2005.

Total Maintenance Costs

Total maintenance costs include the costs of parts and hourly labor costs of $50 per hour, and do <u>not</u> include warranty costs. Cost per mile is calculated as follows:

Cost per mile = ((labor hours * 50) + parts cost)/mileage

The labor rate has been artificially set at a constant rate of $50 per hour so that others can change this rate to one more similar to their own. Also, this rate does not reflect NYCT's current hourly mechanic rate.

Table 11 shows total maintenance costs for the CNG buses at West Farms Depot and Hybrid buses at Mother Clara Hale Depot. Two of the CNG buses had higher total maintenance costs than the other eight CNG buses. These higher costs were caused mostly by brake reline activities. There were two hybrid buses (buses 6367 and 6379) that had total maintenance costs higher than the rest. These higher total maintenance costs were caused by significant repairs troubleshooting the hybrid propulsion system, hydraulic pump, PCS cooling system, doors, and air conditioning. Most of these significant repairs are a part of the aforementioned campaigns for the hybrid buses.

The total maintenance cost for the CNG buses was 8% higher than the hybrid buses. This difference will be explored further in the next discussion about maintenance cost breakdown by vehicle systems.

Table 11. CNG and Hybrid Bus Total Maintenance Costs (Evaluation Period)

Bus	Mileage	Parts ($)	Labor Hours	Cost per Mile ($)
7657	18,708	4,820.41	390.0	1.30
7662	19,419	4,444.86	368.3	1.18
7666	13,087	8,316.46	433.5	2.29
7670	17,938	6,021.11	348.5	1.31
7677	17,993	8,156.55	417.9	1.61
7688	18,516	5,730.23	330.5	1.20
7708	19,344	5,141.26	333.6	1.13
7715	18,313	3,976.66	329.4	1.12
7719	17,483	4,936.99	282.9	1.09
7721	18,746	4,112.70	324.2	1.08
Total CNG	**179,547**	**55,657.23**	**3,558.5**	**1.30**
Avg. per Bus	**17,955**	**5,565.72**	**355.9**	**--**
6367	16,812	4,711.21	391.3	1.44
6368	18,465	2,677.03	396.9	1.22
6369	18,545	3,820.93	400.9	1.29
6375	21,252	2,569.34	384.6	1.03
6378	20,534	3,412.69	386.9	1.11
6379	20,453	5,469.01	479.2	1.44
6380	16,963	2,224.94	282.5	0.96
6381	19,470	3,238.01	396.2	1.18
6382	21,043	2,842.97	407.6	1.10
6387	20,858	3,486.36	393.1	1.11
Total Hybrid	**194,395**	**34,452.49**	**3,919.0**	**1.19**
Avg. per Bus	**19,440**	**3,445.25**	**391.9**	**--**

Maintenance Cost Broken Down by System

Table 12 shows maintenance costs by vehicle system and bus study group. The vehicle systems shown in the tables include the following:

- Preventive maintenance inspections (PMI)—Labor for inspections during preventive maintenance
- Tires
- Propulsion-related systems—Repairs for exhaust; fuel; engine; electric motors, traction batteries, and propulsion control; non-lighting electrical, air intake, cooling, and transmission

- Cab, body, and accessories—Includes body repairs following accidents, glass, and paint; cab and sheet metal repairs on seats and doors; and accessory repairs such as hubodometers and radios
- Frame, steering, and suspension—Includes steering and suspension repairs
- Brakes—Excludes regenerative braking for the hybrids, which is included in propulsion-related systems
- Heating, ventilation, and air conditioning (HVAC)
- Axles, wheels, and drive shaft
- Lighting
- Air System, general
- Hydraulics

Table 13 summarizes the top five maintenance cost categories from the total maintenance breakdown for each study group. Each of the study groups has propulsion-related, cab, body, and accessories, and HVAC costs in the top five. The other two categories that show up in the top five are brakes or frame, steering, and suspension. These categories are discussed in more detail in the following sections.

Table 12. Breakdown of Vehicle System Maintenance Cost per Mile (Evaluation Period)

System	CNG West Farms		Hybrid Mother Clara Hale	
	Cost per Mile ($)	Percent of Total (%)	Cost per Mile ($)	Percent of Total (%)
Cab, Body, and Accessories	0.38	29	0.39	33
Propulsion-related	0.27	21	0.29	25
PMI	0.13	10	0.18	15
Brakes	0.20	16	0.04	3
Frame, Steering, and Suspension	0.05	4	0.07	6
HVAC	0.07	5	0.09	8
Lighting	0.05	4	0.05	4
Air, General	0.07	5	0.04	3
Axles, Wheels, and Drive Shaft	0.04	3	0.01	1
Tires	0.04	3	0.01	1
Hydraulics	0.00	0	0.01	1
Total	**1.30**	**100**	**1.19**	**100**

Table 13. Top 5 Maintenance Cost Categories

Rank	CNG West Farms	Hybrid Mother Clara Hale
1	Cab, Body, and Accessories	Cab, Body, and Accessories
2	Propulsion-related	Propulsion-related
3	Brakes	PMI
4	PMI	HVAC
5	HVAC	Frame, Steering, and Suspension

Propulsion-Related Maintenance Costs

The propulsion-related vehicle systems include the exhaust, fuel, engine, electric propulsion, air intake, cooling, non-lighting electrical, and transmission systems. Table 14 shows the total propulsion-related maintenance costs and lists the costs for the two study groups. Table 15 summarizes the cost comparisons between the study groups. All comparison calculations are hybrid compared to CNG as the baseline.

Total propulsion-related systems maintenance costs for the CNG buses was 9% lower costs than the hybrid buses.

A breakdown of the propulsion-related maintenance costs included:

- **Exhaust system maintenance**—The hybrid bus group had five work orders related to a DPF backpressure issue during the evaluation period. This problem was a result of a software problem in the active monitoring of the DPF in the hybrid buses. When the DPF was removed and cleaned or replaced, the system would recognize that there was a significant change in the backpressure and give a warning indicator light; however, there was no problem. A few exhaust backpressure sensors were replaced before this situation was properly resolved. A software change has been made and this is no longer an issue, but has shown up in the evaluation period. The hybrid buses had exhaust maintenance costs more than twice those of the CNG buses. The CNG buses have had a problem with the thermal blanket on the exhaust wear out from vibration. Five of the ten CNG buses had the thermal blanket replaced during the evaluation period. This issue has not yet been permanently resolved.

- **Fuel system maintenance**— The CNG buses had fuel system maintenance costs 77% higher than the hybrid buses. This difference was mostly due to the extra fuel filter costs for the CNG buses and a few problems with the CNG fuel leak sensors.

- **Engine system maintenance costs**—The CNG buses had engine system maintenance costs 2% higher than the hybrid buses. The CNG buses were reported to have high engine oil consumption. This extra cost was not captured here. The CNG engines are in the process of being rebuilt as a campaign with new cylinder kits along with new spark plugs.

- **Electric propulsion systems maintenance costs**—These costs pertain only to the hybrid buses at Mother Clara Hale. Most of these maintenance issues for the hybrid buses had to do with troubleshooting the hybrid control system and learning to diagnose electric propulsion system failures. Some of the problems reported in the maintenance system included the PCS cooling system, triple pump, filters, traction battery, and traction motor. Troubleshooting work orders in this category included "won't start" and "check" or "stop" hybrid electric vehicle HEV lights.

  During the evaluation period (October 2004 through May 2005), the hybrid fleet has had several single battery replacements including a few single battery replacements for the hybrid study group. This hybrid fleet of 125 has not incurred a roadcall attributable to the traction batteries. BAE Systems is investigating historical replacement actions to determine root cause and consider whether an opportunity exists to modify procedures or energy storage system monitoring software to improve overall system performance and reliability. This analysis from BAE Systems has been promised for the final evaluation report for the order of 125 hybrid buses.

- **Non-lighting electrical systems maintenance costs**—These costs include general electrical maintenance other than lighting including charging, cranking, and ignition systems. The CNG buses had maintenance costs 58% higher than the hybrid buses.

  The CNG buses had issues with the starter, the main power control and communications systems. The spark plugs on the CNG buses have been an issue with failures as early as 4,000 miles. The CNG engines now use four iridium spark plugs costing $240 for the set. DDC paid for the first set of these iridium spark plugs as part of the CNG engine campaign and now NYCT will be paying for the subsequent changes on a 24,000 mile interval or approximately once per year. Only one set of these new spark plugs were accounted for during the evaluation period, and more are expected in the final results report. NYCT reports that the new spark plugs are working much better so far.

  Issues for the hybrid buses in this category included the voltage regulator, alternator, and wiring.

- **Air intake system maintenance costs**—The CNG buses had maintenance costs 38% higher than the hybrid buses. There were no major problems or issues for either fleet in this category.

- **Cooling system maintenance costs**—The CNG buses had maintenance costs 13% higher than the hybrid buses.

- **Transmission system maintenance costs**—The hybrid buses do not have a transmission. The CNG buses did not have any significant transmission repairs during the evaluation period.

Table 14. Propulsion-Related Maintenance Cost by System (Evaluation Period)

Maintenance System Costs	CNG West Farms	Hybrid Mother Clara Hale
Mileage	179,547	194,395
Total Propulsion-related Systems (Roll-Up)		
Parts Cost ($)	14,207.96	6,336.75
Labor Hours	680.5	1,012.8
Total Cost ($)	48,232.96	56,974.25
Total Cost ($) per Mile	**0.27**	**0.29**
Exhaust System Repairs		
Parts Cost ($)	659.38	624.00
Labor Hours	37.0	102.7
Total Cost ($)	2,509.38	5,759.00
Total Cost ($) per Mile	**0.01**	**0.03**
Fuel System Repairs		
Parts Cost ($)	2,744.56	753.57
Labor Hours	99.4	24.0
Total Cost ($)	7,714.56	1,953.57
Total Cost ($) per Mile	**0.04**	**0.01**
Engine System Repairs		
Parts Cost ($)	2,266.44	1,606.98
Labor Hours	126.6	151.1
Total Cost ($)	8,596.44	9,159.48
Total Cost ($) per Mile	**0.05**	**0.05**
Electric Motor, Generator, and Battery Repairs		
Parts Cost ($)		1,937.07
Labor Hours		462.0
Total Cost ($)		24,962.07
Total Cost ($) per Mile		**0.13**
Non-Lighting Electrical System Repairs (General Electrical, Charging, Cranking, Ignition)		
Parts Cost ($)	4,101.95	622.37
Labor Hours	263.3	143.0
Total Cost ($)	17,266.95	7,772.37
Total Cost ($) per Mile	**0.10**	**0.04**
Air Intake System Repairs		
Parts Cost ($)	1,439.59	754.11
Labor Hours	8.0	9.5
Total Cost ($)	1,839.59	1,229.11
Total Cost ($) per Mile	**0.01**	**0.01**
Cooling System Repairs		
Parts Cost ($)	1,430.27	38.65
Labor Hours	99.8	120.5
Total Cost ($)	6,417.77	6,063.65
Total Cost ($) per Mile	**0.04**	**0.03**
Transmission Repairs		
Parts Cost ($)	1,565.77	
Labor Hours	46.5	
Total Cost ($)	3,888.27	
Total Cost ($) per Mile	**0.02**	

Table 15. Summary of Propulsion-Related Maintenance Cost Comparisons*

System	Hybrid vs. CNG
Total Propulsion-related	**9% (higher)**
Exhaust	111% (higher)
Fuel	-77% (lower)
Engine	-2% (lower or same)
Electric Propulsion	N/A
Non-Lighting Electrical	-58% (lower)
Air Intake	-38% (lower)
Cooling	-13% (lower)
Transmission	N/A

* The cost comparisons are provided as hybrid compared to CNG as the baseline.
((Hybrid cost per mile/CNG cost per mile) – 1) * 100% = Percent comparison
For example, the total propulsion related entry is 9% higher, this is hybrid costs being 9% higher than CNG for this category.

Figure 17 shows the monthly propulsion-related maintenance cost per mile for the CNG and hybrid buses. Each study group's maintenance cost per mile is shown as an average for the month and cumulative average for the evaluation period. The cumulative average propulsion-related maintenance cost per mile for the hybrid and CNG buses have been tracking together for the last three or four months of the evaluation period and end up with the hybrid buses being 9% higher (as mentioned above).

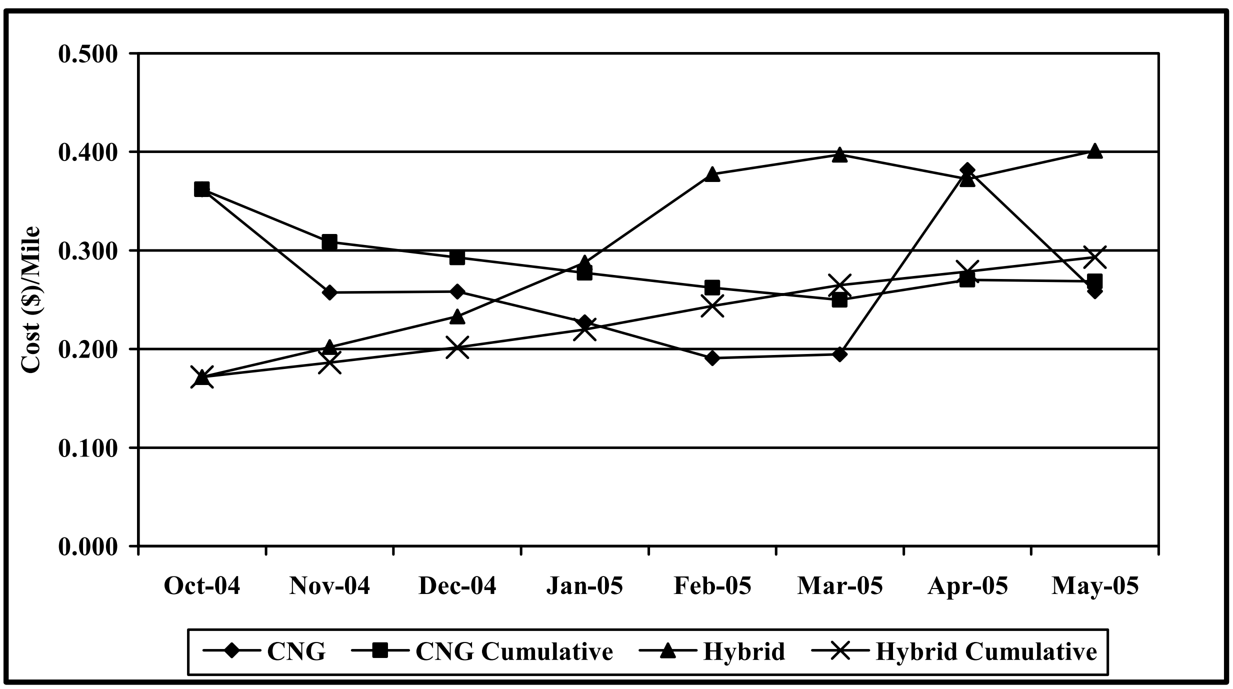

Figure 17. Propulsion-Related Maintenance Cost per Mile for CNG and Hybrid Buses

The maintenance costs of the CNG bus group have generally been decreasing for the propulsion-related systems. There was one peak in the monthly average cost per mile around April 2005, which was caused by several isolated repair actions on different buses. These repair actions included the accelerator, two major engine repairs, one significant charging repair, one multiplexer/communications system repair, one exhaust system repair, and one significant transmission repair. All of these actions appear to coincidentally occur in April 2005 and do not appear to be related.

For the hybrid buses, the monthly maintenance costs for propulsion-related systems steadily increased during the evaluation period. The maintenance issues appear to mostly involve the hybrid propulsion control system and the engine. In April 2005, there was a traction battery replacement (bus 6382) and a triple pump replaced (bus 6375). There were significant cooling and exhaust/DPF repairs as well. The increased propulsion-related maintenance costs were most likely related to an investment in mechanic time for troubleshooting and on-the-job training. This is an indication of the depot staff coming up to speed in how to repair the hybrid buses on their own. This level of mechanic time may decrease over time as the mechanics become more experienced with the hybrid buses.

Cab, Body, and Accessories Systems
The vehicle systems included in this grouping are shown in Table 16. The maintenance costs associated with these systems are shown by bus study group. The following bullets describe each of the subsystem divisions chosen to break down this category.

- Door and interlock—Includes anything that has to do with the doors and interlock system except for the brakes
- Wheelchair lift/ramp—Includes all repairs for the wheelchair lift or ramp systems, except hydraulics
- Body exterior—Includes all body panels and compartment doors, as well as reflectors
- Cleaning—All cleaning activities inside and outside the bus
- Mirrors—All inside and outside mirrors
- General interior and seats
- Windshield wipers—Includes the wipers, motors, and washer systems
- Supplies and expendable items—Includes painting supplies, tools, wipes, eyeglasses, and coveralls assigned to a bus
- Destination signs
- Horn
- Farebox
- Fire extinguisher
- Radio

The CNG and hybrid bus study groups had essentially the same cost per mile for this category. The breakdown of the makeup of the subdivision costs is slightly different for each bus group.

Table 16. Breakdown of Cab, Body, and Accessory Maintenance Cost per Mile (Evaluation Period)

Subsystem	CNG West Farms		Hybrid Mother Clara Hale	
	Cost per Mile ($)	Percent (%)	Cost per Mile ($)	Percent (%)
Doors and Interlock	0.05	13	0.11	28
Wheelchair Lift / Ramp	0.04	11	0.04	9
Body—Exterior	0.13	34	0.09	23
Cleaning	0.07	18	0.06	15
Mirrors	0.02	6	0.03	8
General Interior and Seats	0.03	8	0.03	8
Windshield Wipers	0.02	6	0.01	3
Supplies and expendable items	0.00	0	0.00	0
Destination Sign	0.00	0	0.00	0
Horn	0.01	4	0.01	3
Farebox	0.00	0	0.00	0
Fire Extinguisher	0.00	0	0.01	3
Radio	0.00	0	0.00	0
Total	**0.38**	**100**	**0.39**	**100**

HVAC

This category includes all maintenance actions for heating and ventilation and the air conditioning system. The majority of the costs in this category are typically related to the air conditioning. The maintenance costs for the two study groups are shown in Table 17. The maintenance cost per mile for the two study groups are about the same with the CNG buses being 29% lower than for the hybrid buses. For the hybrid buses during the evaluation period, eight of the 10 buses had an inspection and repairs that took 16 hours of mechanic time each.

Table 17. HVAC System Maintenance Costs (Evaluation Period)

Fleet	Mileage	Parts Cost ($)	Labor Hours	Cost per Mile ($)
West Farms CNG	179,547	3,715.98	182.6	0.07
Mother Clara Hale Hybrid	194,395	1,906.13	321.5	0.09

Brakes

The brake system maintenance costs are expected to be dramatically lower for hybrid propulsion systems with regenerative braking. The regenerative braking allows the electric drive motors to be used to slow down a bus like a transmission retarder. The energy from braking is taken into the electric motor and then fed back to the traction batteries. Diesel and CNG buses are expected to have a four-wheel reline of the brakes every 18,000 miles on average.

Table 18 shows the maintenance costs for the brake system repairs for the two study bus groups. During the evaluation period, the CNG buses had 82% higher brake maintenance cost per mile compared to the hybrid buses. The five oldest CNG buses in the study group had at least one four-wheel reline of the brakes during the evaluation period. One of those five CNG buses had the four-wheel reline twice within three months. There were also some repairs for issues with the antilock brake system for the CNG and hybrid buses. More data is required for the hybrid buses to fully understand how much longer the hybrid buses can go between brake relines and what that cost savings might ultimately be.

Table 18. Brake System Maintenance Costs (Evaluation Period)

Fleet	Mileage	Parts Cost ($)	Labor Hours	Cost per Mile ($)
West Farms CNG	179,547	9,571.28	536.3	0.20
Mother Clara Hale Hybrid	194,395	1,373.64	116.9	0.04

PMI

This category only includes labor hours for inspections of multiple bus systems during preventive maintenance. As shown in Table 19, the CNG buses have PMI maintenance cost per mile 38% lower than the hybrid buses. However, for all maintenance costs per mile for scheduled maintenance, the CNG and hybrid buses had exactly the same cost at $0.29 per mile. The scheduled maintenance costs include filters and materials used as part of scheduled maintenance. One note here would be that some of the preventive maintenance parts for the hybrid buses may have been paid for under warranty and not accounted for in this cost per mile measure.

Table 19. Preventive Maintenance Inspection Maintenance Costs (Evaluation Period)

Fleet	Mileage	Parts Cost ($)	Labor Hours	Cost per Mile ($)
West Farms CNG	179,547	0.00	465.7	0.13
Mother Clara Hale Hybrid	194,395	0.00	695.0	0.18

Frame, Steering, and Suspension

This category includes repairs for the frame, steering, and suspension systems of the buses. As shown in Table 20, the CNG buses had maintenance cost per mile 25% lower than the hybrid buses.

Table 20. Frame, Steering, and Suspension Maintenance Costs (Evaluation Period)

Fleet	Mileage	Parts Cost ($)	Labor Hours	Cost per Mile ($)
West Farms CNG	179,547	2,490.77	139.9	0.05
Mother Clara Hale Hybrid	194,395	3,717.55	182.2	0.07

Warranty Costs

Maintenance costs that were covered under warranty were generally removed. NYCT requested that suppliers working on the CNG and hybrid buses enter mechanic time into the maintenance system. These labor hours were not included in the analyses presented in this report. The CNG buses had 45.2 labor hours removed from the analysis in this report and the hybrid buses had 96.25 labor hours removed. These labor hours were from Atlantic Detroit Diesel Allison (local dealer), Cummins, Vapor Corporation, and Orion.

There are some repairs and parts costs that are most likely included in these analyses; however, there was no indication in the NYCT maintenance system to make a decision to remove the data. As an action item for the final report, an investigation of available information on warranty claims will be made. If more information regarding warranty claims can be found, the confirmed costs claimed on warranty will be removed.

Roadcall Analysis

Figure 18 shows the cumulative average miles between roadcalls (MBRC) for all RCs for the CNG, Hybrid, and two diesel baseline fleets. With an average of 2,000 MBRC, the diesel buses at West Farms are well below NYCT's expectation that all buses should meet or exceed 4,000 MBRC. Both the diesel buses at Mother Clara Hale Depot and the CNG buses are above the goal at around 5,000 MBRC. The MBRC of the hybrid buses has started to settle around 7,000 MBRC—well above the MBRC of the other three study groups.

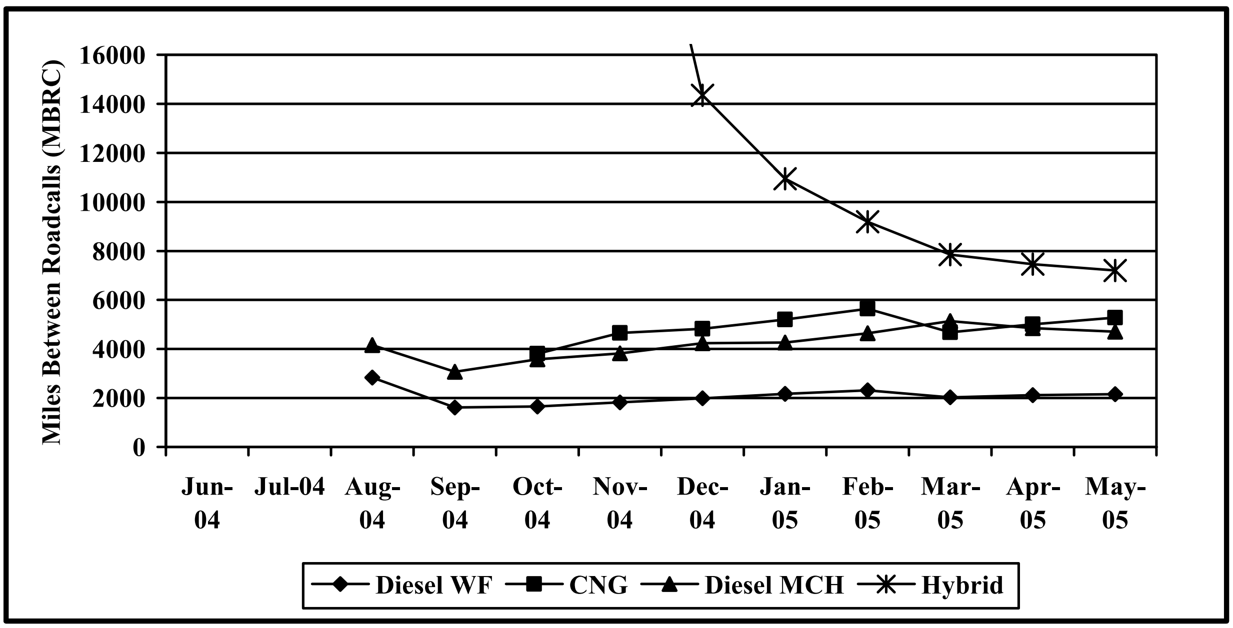

Figure 18. Cumulative Average MBRC

Figure 19 shows MBRC for RCs that involved the propulsion-related systems in all four of the study groups. Propulsion-related systems include the transmission, non-lighting electrical (general electrical, charging, cranking, and ignition), air intake, cooling, exhaust, fuel, engine, and electrical propulsion. RCs for June 2004 and July 2004 were not available for the diesel buses and are not included in the figure.

The CNG buses had a RC rate 56% better than the diesel buses at West Farms Depot. The hybrid and diesel buses at Mother Clara Hale Depot have essentially the same rate with the hybrid group at 2% higher. The hybrid buses have a rate 38% higher than the CNG buses.

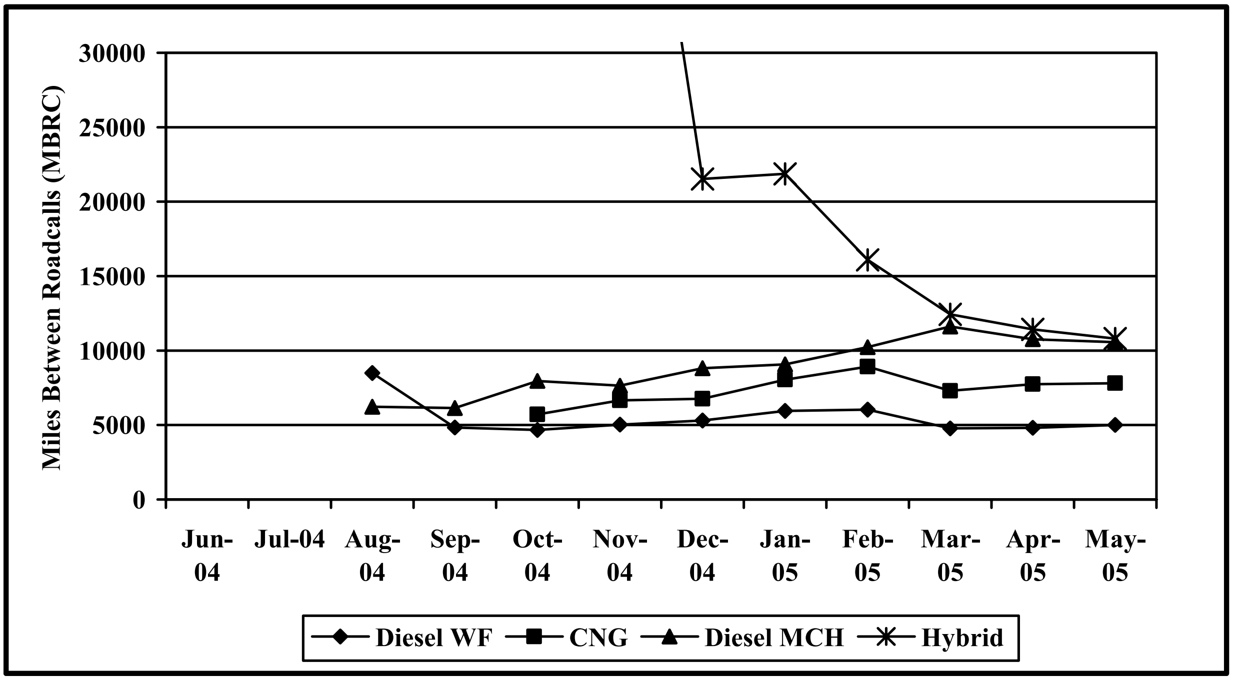

Figure 19. Cumulative Average MBRC, Propulsion-Related Only

Table 21 provides a summary of the RCs for each study group of buses for the evaluation period. The diesel buses at West Farms had the most RCs for doors and interlock, cooling (hydraulic fan), and engine. The CNG buses had the most RCs for non-lighting electrical (mostly for problems starting), doors and interlock, and engine. The diesel buses at Mother Clara Hale had the most RCs for doors and interlock, non-lighting electrical, and wheelchair lift/ramp. The hybrid buses had the most RCs for the electric propulsion system and air system. The electric propulsion system RCs were mostly caused by “check” or “stop” HEV lights.

Table 21. Roadcalls for Each Fleet by System (Evaluation Period)

System	Diesel West Farms		CNG West Farms		Diesel Mother Clara Hale		Hybrid Mother Clara Hale	
	RCs	Percent (%)	RCs	Percent (%)	RCs	Percent (%)	RCs	Percent (%)
HVAC	3	4	0	0	1	2	3	9
Door and Interlock	16	22	7	20	10	22	3	9
Mirrors and Sun Visor	1	1	0	0	0	0	0	0
Air-General	1	1	0	0	1	2	4	14
Brakes	2	3	0	0	0	0	1	3
Steering	3	4	0	0	1	2	0	0
Suspension	2	3	2	6	2	5	0	0
Transmission*	3	4	1	3	1	2	0	0
Non-Lighting Electrical*	5	7	12	35	6	13	2	6
Lighting	0	0	1	3	2	5	0	0
Cooling*	16	22	1	3	5	11	2	6
Exhaust*	2	3	0	0	2	5	0	0
Fuel*	2	3	3	9	4	9	0	0
Engine*	10	14	6	18	4	9	2	6
Electric Propulsion*	0	0	0	0	0	0	14	44
Wheelchair Lift/Ramp	6	9	1	3	6	13	1	3
Total	**72**	**100**	**34**	**100**	**45**	**100**	**32**	**100**

Summary of Costs

Table 22 summarizes fuel and maintenance cost per mile for the CNG and hybrid study groups. The hybrid buses have a cost per mile 28% lower than the CNG buses. This lower cost is due almost entirely to the difference in the fuel economies of the hybrid and CNG buses.

Table 22. Summary of Cost per Mile for CNG and Hybrid Buses (Evaluation period)

Bus	Fuel Cost / Mile ($)	Maintenance Cost / Mile ($)	Total Cost / Mile ($)
7657	1.03	1.30	2.33
7662	0.95	1.18	2.13
7666	1.04	2.29	3.33
7670	1.05	1.31	2.36
7677	1.03	1.61	2.64
7688	1.07	1.20	2.27
7708	1.09	1.13	2.22
7715	1.02	1.12	2.14
7719	1.11	1.09	2.20
7721	1.01	1.08	2.09
CNG	**1.04**	**1.30**	**2.34**
6367	0.49	1.44	1.93
6368	0.51	1.22	1.73
6369	0.48	1.29	1.77
6375	0.49	1.03	1.52
6378	0.48	1.11	1.59
6379	0.50	1.44	1.94
6380	0.53	0.96	1.49
6381	0.48	1.18	1.66
6382	0.49	1.10	1.59
6387	0.50	1.11	1.61
Hybrid	**0.49**	**1.19**	**1.68**

What's Next?

This interim evaluation report represents eight out of 12 months of evaluation planned for the CNG and hybrid buses (from the order of 125). The final results of these two study groups will be complete with data through September 2005 and should be reported in early calendar year 2006.

NYCT has also taken delivery of nearly all of an order of 200 more hybrid buses from Orion and BAE Systems. As of September 2005, 182 of the 200 buses had been delivered to NYCT for service. The 200 new hybrid buses are being split between Fresh Pond Depot in Brooklyn (138) and Manhattanville Depot in Manhattan (62). These buses will be evaluated with a selection of hybrid and diesel baseline buses at Manhattanville Depot. The interim report from this evaluation should also be available in 2006.

NYCT has recently placed another large order of diesel hybrid buses from Orion and BAE Systems including 500 hybrid buses with the option to purchase up to a total of 889 buses. NYCT is expecting to take delivery of 216 of these hybrid buses and 284 hybrid buses are for their sister agency, MTA Buses. NYCT intends to add hybrid bus operations to the East New York and Casey Stengel depots as well as converting the entire Manhattanville Depot to only diesel hybrid bus operation.

The purchase price of these hybrid buses was a little less than $500,000 each, which is reportedly about $150,000 more than a new standard clean diesel bus.

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Acronyms and Abbreviations

AVTA—Advanced Vehicle Testing Activity
bhp—brake horsepower
CNG—compressed natural gas
CO—carbon monoxide
DDC—Detroit Diesel Corporation
DOC—diesel oxidation catalyst
DOE—U.S. Department of Energy
DPF—diesel particulate filter
EPA—U.S. Environmental Protection Agency
EGR—exhaust gas recirculation
g/bhp-hr—grams per brake horsepower hour
HC—hydrocarbons
HEV—hybrid electric vehicle
HVAC—heating, ventilation, and air conditioning
LIRR—Long Island Railroad
LI Bus—Long Island Bus
MBRC—miles between roadcalls
MCH—Mother Clara Hale Depot
MTA—Metropolitan Transportation Authority
NREL—National Renewable Energy Laboratory
NYCT—New York City Transit
NMHC—non-methane hydrocarbons
NOx—oxides of nitrogen
PCS—power control system
PM—particulate matter
ppm—parts per million
PMI—preventive maintenance inspection
RC—roadcall
R&D—research and development
rpm—revolutions per minute
scfm—standard cubic feet per minute
SCR—selective catalytic reduction
ULSD—ultra low sulfur diesel

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Appendix: Fleet Summary Statistics

Appendix A: Summary of Diesel, CNG, and Hybrid Results

Fleet Operations and Economics

	WF Diesel	WF CNG (Eval)	MCH Diesel	MCH Hybrid (Eval)
Number of Vehicles	9	10	9	10
Period Used for Fuel and Oil Op Analysis	6/04-5/05	10/04-5/05	6/04-5/05	10/04-5/05
Total Number of Months in Period	12	8	12	8
Fuel and Oil Analysis Base Fleet Mileage	186,682	163,763	249,990	168,027
Period Used for Maintenance Op Analysis	6/04-5/05	10/04-5/05	6/04-5/05	10/04-5/05
Total Number of Months in Period	12	8	12	8
Maintenance Analysis Base Fleet Mileage	191,264	179,547	257,624	194,395
Average Monthly Mileage per Vehicle	1,952	2,244	2,385	2,430
Fleet CNG/Diesel Equiv. Usage in Gal.	82,019	95,650	105,138	48,849
Representative Fleet MPG (energy equiv)	2.28	1.71	2.38	3.44
Diesel Cost per gallon	1.70	1.78	1.70	1.70
Fuel Cost per Mile	**0.75**	**1.04**	**0.72**	**0.49**
Total Scheduled Repair Cost per Mile	0.30	0.29	0.30	0.29
Total Unscheduled Repair cost per Mile	1.97	1.01	1.45	0.90
Total Maintenance Cost per Mile	**2.27**	**1.30**	**1.75**	**1.19**
All Roadcalls	**72**	**34**	**45**	**27**
MBRC for All Roadcalls	**2,154**	**5,281**	**4,701**	**7,200**
Propulsion-Related Roadcalls	**31**	**23**	**20**	**18**
MBRC for Propulsion-Related Roadcalls	**5,002**	**7,806**	**10,576**	**10,800**

Appendix B: CNG (Orion VII) at West Farms Depot and Hybrid (Orion VII) at Mother Clara Hale Depot

Fleet Operations and Economics

	CNG (Eval)	Hybrid (Eval)
Number of Vehicles	10	10
Period Used for Fuel and Oil Op Analysis	10/04-5/05	10/04-5/05
Total Number of Months in Period	8	8
Fuel and Oil Analysis Base Fleet Mileage	163,763	168,027
Period Used for Maintenance Op Analysis	10/04-5/05	10/04-5/05
Total Number of Months in Period	8	8
Maintenance Analysis Base Fleet Mileage	179,547	194,395
Average Monthly Mileage per Vehicle	2,244	2,430
Fleet Diesel Usage in Gal.	95,650	48,849
Representative Fleet MPG (energy equiv)	1.71	3.44
Diesel Cost per gallon	1.78	1.70
Fuel Cost per Mile	**1.04**	**0.49**
Total Scheduled Repair Cost per Mile	0.29	0.29
Total Unscheduled Repair cost per Mile	1.01	0.90
Total Maintenance Cost per Mile	**1.30**	**1.19**
Total Operating Cost per Mile	**2.34**	**1.68**

Maintenance Costs

	CNG (Eval)	Hybrid (Eval)
Fleet Mileage	179,547	194,395
Total Parts Cost	55,657.23	34,452.49
Total Labor Hours	3558.9	3919.0
Average Labor Cost (@ $50.00 per hour)	177,945.00	195,950.00
Total Maintenance Cost	233,602.23	230,402.49
Total Maintenance Cost per Bus	23,360.22	23,040.25
Total Maintenance Cost per Mile	**1.30**	**1.19**

Breakdown of Maintenance Costs by Vehicle System

	CNG (Eval)	Hybrid (Eval)
Fleet Mileage	257,624	194,395
Total Engine/Fuel-Related Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46)		
Parts Cost	14,207.96	6,336.75
Labor Hours	680.5	1012.8
Average Labor Cost	34,025.00	50,637.50
Total Cost (for system)	48,232.96	56,974.25
Total Cost (for system) per Bus	4,823.30	5,697.43
Total Cost (for system) per Mile	**0.27**	**0.29**
Exhaust System Repairs (ATA VMRS 43)		
Parts Cost	659.38	624.00
Labor Hours	37.0	102.7
Average Labor Cost	1,850.00	5,135.00
Total Cost (for system)	2,509.38	5,759.00
Total Cost (for system) per Bus	250.94	575.90
Total Cost (for system) per Mile	**0.01**	**0.03**
Fuel System Repairs (ATA VMRS 44)		
Parts Cost	2,744.56	753.57
Labor Hours	99.4	24.0
Average Labor Cost	4,970.00	1,200.00
Total Cost (for system)	7,714.56	1,953.57
Total Cost (for system) per Bus	771.46	195.36
Total Cost (for system) per Mile	**0.04**	**0.01**
Power Plant (Engine) Repairs (ATA VMRS 45)		
Parts Cost	2,266.44	1,606.98
Labor Hours	126.6	151.1
Average Labor Cost	6,330.00	7,552.50
Total Cost (for system)	8,596.44	9,159.48
Total Cost (for system) per Bus	859.64	915.95
Total Cost (for system) per Mile	**0.05**	**0.05**
Electric Propulsion Repairs (ATA VMRS 46)		
Parts Cost	0.00	1,937.07
Labor Hours	0.0	460.5
Average Labor Cost	0.00	23,025.00
Total Cost (for system)	0.00	24,962.07
Total Cost (for system) per Bus	0.00	2,496.21
Total Cost (for system) per Mile	**0.00**	**0.13**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)		
Parts Cost	4,101.95	622.37
Labor Hours	263.3	143.0
Average Labor Cost	13,165.00	7,150.00
Total Cost (for system)	17,266.95	7,772.37
Total Cost (for system) per Bus	1,726.70	777.24
Total Cost (for system) per Mile	**0.10**	**0.04**

Breakdown of Maintenance Costs by Vehicle System (continued)

	CNG (Eval)	Hybrid (Eval)
Air Intake System Repairs (ATA VMRS 41)		
Parts Cost	1,439.59	754.11
Labor Hours	8.0	9.5
Average Labor Cost	400.00	475.00
Total Cost (for system)	1,839.59	1,229.11
Total Cost (for system) per Bus	183.96	122.91
Total Cost (for system) per Mile	**0.01**	**0.01**
Cooling System Repairs (ATA VMRS 42)		
Parts Cost	1,430.27	38.65
Labor Hours	99.8	120.5
Average Labor Cost	4,987.50	6,025.00
Total Cost (for system)	6,417.77	6,063.65
Total Cost (for system) per Bus	641.78	606.37
Total Cost (for system) per Mile	**0.04**	**0.03**
Hydraulic System Repairs (ATA VMRS 65)		
Parts Cost	0.00	1,599.02
Labor Hours	5.2	17.0
Average Labor Cost	260.00	850.00
Total Cost (for system)	260.00	2,449.02
Total Cost (for system) per Bus	26.00	244.90
Total Cost (for system) per Mile	**0.00**	**0.01**
General Air System Repairs (ATA VMRS 10)		
Parts Cost	7,885.04	3,594.15
Labor Hours	79.5	88.3
Average Labor Cost	3,972.50	4,412.50
Total Cost (for system)	11,857.54	8,006.65
Total Cost (for system) per Bus	1,185.75	800.67
Total Cost (for system) per Mile	**0.07**	**0.04**
Brake System Repairs (ATA VMRS 13)		
Parts Cost	9,571.28	1,373.64
Labor Hours	536.3	116.9
Average Labor Cost	26,812.50	5,842.50
Total Cost (for system)	36,383.78	7,216.14
Total Cost (for system) per Bus	3,638.38	721.61
Total Cost (for system) per Mile	**0.20**	**0.04**
Transmission Repairs (ATA VMRS 27)		
Parts Cost	1,565.77	0.00
Labor Hours	46.5	1.5
Average Labor Cost	2,322.50	75.00
Total Cost (for system)	3,888.27	75.00
Total Cost (for system) per Bus	388.83	7.50
Total Cost (for system) per Mile	**0.02**	**0.00**

Breakdown of Maintenance Costs by Vehicle System (continued)

	CNG (Eval)	Hybrid (Eval)
Inspections Only - no parts replacements (101)		
Parts Cost	0.00	0.00
Labor Hours	465.7	695.0
Average Labor Cost	23,282.50	34,750.00
Total Cost (for system)	23,282.50	34,750.00
Total Cost (for system) per Bus	2,328.25	3,475.00
Total Cost (for system) per Mile	**0.13**	**0.18**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)		
Parts Cost	15,426.32	14,158.72
Labor Hours	1045.7	1237.5
Average Labor Cost	52,282.50	61,875.00
Total Cost (for system)	67,708.82	76,033.72
Total Cost (for system) per Bus	6,770.88	7,603.37
Total Cost (for system) per Mile	**0.38**	**0.39**
HVAC System Repairs (ATA VMRS 01)		
Parts Cost	3,715.98	1,906.13
Labor Hours	182.6	321.5
Average Labor Cost	9,130.00	16,075.00
Total Cost (for system)	12,845.98	17,981.13
Total Cost (for system) per Bus	1,284.60	1,798.11
Total Cost (for system) per Mile	**0.07**	**0.09**
Lighting System Repairs (ATA VMRS 34)		
Parts Cost	2,046.57	1,623.43
Labor Hours	146.7	172.7
Average Labor Cost	7,332.50	8,635.00
Total Cost (for system)	9,379.07	10,258.43
Total Cost (for system) per Bus	937.91	1,025.84
Total Cost (for system) per Mile	**0.05**	**0.05**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)		
Parts Cost	2,490.77	3,717.55
Labor Hours	139.9	182.2
Average Labor Cost	6,995.00	9,110.00
Total Cost (for system)	9,485.77	12,827.55
Total Cost (for system) per Bus	948.58	1,282.76
Total Cost (for system) per Mile	**0.05**	**0.07**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)		
Parts Cost	313.31	143.10
Labor Hours	127.9	38.0
Average Labor Cost	6,395.00	1,897.50
Total Cost (for system)	6,708.31	2,040.60
Total Cost (for system) per Bus	670.83	204.06
Total Cost (for system) per Mile	**0.04**	**0.01**

Breakdown of Maintenance Costs by Vehicle System (continued)

	CNG (Eval)	Hybrid (Eval)
Tire Repairs (ATA VMRS 17)		
Parts Cost	0.00	0.00
Labor Hours	148.8	37.3
Average Labor Cost	7,437.50	1,865.00
Total Cost (for system)	7,437.50	1,865.00
Total Cost (for system) per Bus	743.75	186.50
Total Cost (for system) per Mile	**0.04**	**0.01**

Notes

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

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

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

4. ATA VMRS 02-cab and sheet metal represents seats, doors, etc. ATA VMRS 50-accessories represents things like 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.

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
January 2006	Technical Report	

4. TITLE AND SUBTITLE	
New York City Transit Hybrid and CNG Transit Buses: Interim Evaluation Results	5a. CONTRACT NUMBER DE-AC36-99-GO10337
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) K. Chandler, E. Eberts, and L. Eudy	5d. PROJECT NUMBER NREL/TP-540-38843
	5e. TASK NUMBER FC06.3000
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	NREL/TP-540-38843
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) NREL
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

This report focuses on the evaluation of compressed natural gas (CNG) and diesel hybrid electric bus propulsion systems in New York City Transit's transit buses.

15. SUBJECT TERMS

New York City Transit (NYCT); compressed natural gas (CNG); hybrid electric; diesel; transit buses; U.S. Department of Energy; evaluation

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
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