Hybrid-Electric Transit Buses

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

NYCT Diesel Hybrid-Electric Buses

Final Results

NEW YORK CITY TRANSIT DIESEL HYBRID-ELECTRIC BUSES: FINAL RESULTS

DOE/NREL Transit Bus Evaluation Project

by

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July 2002

The authors wish to acknowledge the help and cooperation of the staff at the host site, New York City Transit, especially significant input from Dana Lowell and Bill Parsley. Tom Webb from BAE SYSTEMS provided significant input for this evaluation effort. The authors also acknowledge the editorial contributions of Vincent Brown at Battelle and Jarett Zuboy at NREL.

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Executive Summary

New York City Transit (NYCT), part of the Metropolitan Transportation Authority in New York, began operating the first of 10 heavy-duty diesel hybrid-electric transit bus prototypes (Model VI) from Orion Bus Industries in 1998. All 10 buses were in revenue service by mid-2000. The hybrid buses are intended to provide NYCT with increased fuel economy and lower levels of harmful exhaust emissions, compared with NYCT's diesel transit buses.

Between 1999 and 2001 (over various predefined fuel and maintenance evaluation periods), these first 10 hybrid buses were part of a data collection and analysis project sponsored by the U.S. Department of Energy (DOE). The operating costs, efficiency, emissions, and overall performance of these low-floor hybrid buses were compared against those of 14 conventional high-floor diesel transit buses (7 each from NovaBUS Corporation and Orion) operated by NYCT in similar service.

Results indicate that the hybrid buses operate with greater fuel efficiency and much lower emissions, compared with the diesel buses. Maintenance costs for the prototype hybrid buses were significantly higher than those of the diesel buses during this evaluation. However, these costs are expected to decline for the next-generation Orion VII buses, currently being procured by NYCT, as repair technicians become more familiar with the advanced hybrid propulsion systems.

Objective

The objective of the DOE research project, managed by the National Renewable Energy Laboratory (NREL), was to provide transportation professionals with quantitative, unbiased information on the cost, maintenance, operational, and emission characteristics of diesel hybrid-electric systems as one alternative to conventional diesel engines for heavy-duty transit bus applications.

In addition, this information should benefit decision makers by providing a real-world account of the obstacles that were encountered and overcome and the lessons that were learned in adapting hybrid buses to a transit site previously geared toward conventional diesel buses. The field study at NYCT was conducted as part of DOE's ongoing Transit Bus Evaluation Project.

Methods

Data were gathered from fuel and maintenance tracking systems daily for more than 1 year. Examples of the data parameters included:

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

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

Special chassis dynamometer tests of exhaust emissions and fuel efficiency of the hybrid and conventional diesel buses were also conducted.

Goals of the Orion VI Hybrid Fleet

At the time that the 10 Orion VI hybrid buses were delivered, this was the largest standard 40-foot hybrid bus fleet in the United States. Hybrid buses were not a standard configuration for transit applications. BAE SYSTEMS, Orion, and NYCT set out to design, build, and implement the use of hybrid buses into standard transit service. All parties were aware that this was an investment into unproven technology, and this project was intended to develop this technology. NYCT set specific goals for the implementation of hybrid buses in order to measure the success of this development project:

1. Reduce emissions, specifically oxides of nitrogen (NO_x <15 g/mi) and particulate matter (PM <0.06 g/mi)
2. Significantly increase fuel economy
3. Show that the hybrid buses can operate in regular revenue service with no route or driver restrictions
4. Show that the hybrid bus performance (e.g., acceleration, gradability, and range) was equal to or better than that of conventional diesel buses and that drivers can switch from one to the other with no significant difference in operation
5. Demonstrate that drivers and passengers perceive hybrid-electric buses positively
6. Significantly increase brake life
7. Improve the design of the hybrid bus; promote the development of the technology through investment
8. Help put the industry in a position to build and sell "production" hybrid buses.

All indications from the NYCT program and this evaluation show that this implementation of diesel hybrid-electric buses has met or exceeded all goals.

Results

NYCT, BAE SYSTEMS, and Orion are committed to operating the Orion VI diesel hybrid-electric buses in service, as well as the new Orion VII hybrid buses currently on order. The Orion VI hybrid bus has met all basic "White Book" performance expectations and requirements, such as gradability, acceleration, low noise, and emissions.

Facility conversion for accommodating hybrid buses was minor compared to preparing for compressed natural gas (CNG) vehicles.

The hybrid buses had lower mileage (miles driven) on a monthly basis compared to the NovaBUS RTS diesel buses at the same NYCT depot. The reduction in usage of the hybrid buses was a direct result of the need to service the buses and the extra time required to coordinate with the manufacturers to troubleshoot and fix those problems. The lower mileage for the "pre-production" hybrid buses was expected by NYCT and the manufacturers.

The hybrid buses had 10% higher in-service fuel economy on average for the entire evaluation period compared to the NovaBUS RTS diesel buses. Looking at fuel economy per month, the fuel economy advantage of the hybrid buses went as high as 22% during one month of the evaluation period. The hybrid bus fuel economy improved during the evaluation period. No external charging was required for the hybrid buses.

The hybrid buses had a fuel cost per mile 9% lower than the NovaBUS RTS diesel buses.

Chassis dynamometer emission test results with and without regenerative braking on the hybrid buses showed that the fuel economy increase from the hybrid configuration alone is about 6%. Fuel economy is improved even further (23%–64% higher depending on test cycle) through regenerative braking, which stores energy that would otherwise be wasted heat energy in the brakes.

Maintenance costs for the hybrid buses were 76%–150% higher than those of the NovaBUS diesel buses. The maintenance data show that, for the hybrid buses, maintenance costs were much higher for all bus subsystems, even those that have nothing to do with the hybrid propulsion system and are virtually identical to the same subsystems on the diesel buses. This is a strong indication that the cost differences between hybrid and standard diesel will fall significantly for the next generation of vehicles (Orion VII hybrid), which will be deployed in much greater numbers.

For the evaluation period, the hybrid buses had a rate of miles between roadcalls that was 54% lower than the NovaBUS RTS diesel buses for all roadcalls and 80% lower for engine and fuel-related roadcalls.

The hybrid buses had operating costs 46%–92% higher than the NovaBUS RTS diesel buses.

Emission testing at NYCT was conducted by West Virginia University on their mobile chassis dynamometer, for the Northeast Advanced Vehicle Consortium. On the Commercial Business District test cycle, for the hybrid buses compared with the diesel buses, carbon monoxide (CO) was 97% lower, NO_x were 36% lower, hydrocarbons (HC) were 43% lower, PM was 50% lower, and carbon dioxide (CO_2) was 19% lower.

Emission testing was also conducted by Environment Canada on the new Orion VII diesel hybrid buses and the conventional Orion V diesel buses, with and without a catalyzed diesel particulate filter (DPF) installed. The new hybrid bus had 94% lower CO, 49% lower NO_x, 120% higher HC, 93% lower PM, and 37% lower CO_2 than the Orion V diesel without the catalyzed DPF. The new hybrid bus had 38% lower CO, 49% lower NO_x, 450% higher HC, 60% lower PM, and 38% lower CO_2 than the Orion V diesel with the catalyzed DPF.

NYCT has ordered 125 Orion VII diesel hybrid buses to be delivered in 2002 and another 200 Orion VII diesel hybrid buses to be delivered in 2003 and 2004. Fifty more hybrid buses are to be ordered in 2002. NYCT has reported that they are pleased with the progress made to date in developing the heavy-duty diesel hybrid bus into a full-service commercial product to be used in revenue service at the agency.

Lessons Learned

The diesel hybrid-electric bus evaluation project provided NYCT, DOE, and other participants the opportunity to learn many lessons about alternative propulsion systems. Some highlights follow:

- A team effort is required to develop and field test a prototype system into a proven, off-the-shelf system.
- Vendor, manufacturer, and in-house management support are critical during the learning curve at the transit depot, as maintenance personnel diagnose, troubleshoot, and adapt to the new systems, especially when the new systems represent a small fraction of the total bus population at the depot.
- Operators reported that the hybrid buses had better acceleration, better traction in bad weather, and smooth braking.
- Riders noticed the quieter ride, and many expressed interest and enthusiasm in the "electric power" system on the buses.
- Some obstacles to the commercial growth of hybrid bus technology include the performance of current lead-acid batteries, the availability of medium-duty engines certified for transit bus applications, and the high purchase cost of the first generation of production vehicles. This high purchase cost is exacerbated by the small size of the transit bus market, which cannot support the development of new technologies on its own.
- The prospects for greater commercial success would be improved by the availability of low-cost advanced energy storage devices and lower production costs based on the increased production volume that may result from greater penetration of the truck and military markets.

Obstacles Overcome

A number of changes to equipment and software were made in the course of project start-up at NYCT. These upgrades helped the later Orion VI hybrid buses, and all improvements are being incorporated into the design of the new Orion VII hybrid buses ordered by NYCT from Orion. These changes and upgrades were expected for these pre-production vehicles and are consistent with the first generation of a maturing technology.

Future Diesel Hybrid-Electric Operations at NYCT

NYCT has continued its commitment to a cleaner emission fleet of buses. The NYCT bus fleet currently consists of 4,489 buses:

- 10 diesel hybrid-electric
- 221 CNG
- 4,258 diesel.

NYCT plans to purchase more CNG and hybrid buses as well as retrofit the remaining diesel buses with catalyzed DPFs. The bus fleet at NYCT in 2006 will consist of the following buses:

- 385 diesel hybrid-electric
- 646 CNG
- 3,458 diesel with catalyzed DPFs.

The next fleet of hybrid buses at NYCT (an order of 125 Orion VII hybrid buses) is expected to be a nearly full-service, commercial product for NYCT (delivery planned to start in mid-2002). The Orion VII hybrid bus has been designed to incorporate all of the technical lessons learned from the experience with the Orion VI pilot hybrid buses.

The Orion VII diesel hybrid-electric bus design is expected to be more fully optimized for fuel economy and emissions. With the new order of 125 Orion VII diesel hybrid-electric buses at NYCT, the goals of their hybrid program have progressed. The goals for the operation of the newer hybrid buses are similar to those for the original 10 buses but are now more focused on reliability and optimization for cost of operations:

1. Continue to significantly reduce bus fleet emissions
2. Continue to significantly increase fuel economy
3. Show that the hybrid buses are commercially viable, i.e., hybrids can be purchased in volume with standard terms and conditions to replace conventional diesel buses
4. Demonstrate rapid deployment of a large number of hybrid buses with minimal infrastructure investment or service capacity interruptions
5. Demonstrate that hybrid buses can be reliable and cost-effective in providing regular revenue service.

NREL plans to implement a follow-up evaluation of the Orion VII hybrid bus order at NYCT, starting as soon as early 2003.

NYCT is converting various depots to accommodate hybrid and CNG buses and has specified ultra-low sulfur diesel (less than 30 ppm sulfur) fuel for all of its diesel operations. A new capital spending plan for NYCT will be finalized in 2004 for bus purchases from 2005 through 2009. This plan may include more CNG, hybrid, and possibly fuel cell bus purchases (at least for demonstration purposes).

Overview

New York City Transit (NYCT) is a part of the Metropolitan Transportation Authority (MTA) in New York. NYCT is the largest agency in the MTA and includes more buses than any other public agency in North America. Its area of operation and bus terminal locations are shown in Figure 1.

NYCT started a pilot test of diesel hybrid-electric buses in 1998 with the first 4 of 10 buses it would eventually receive from Orion. This fleet of 10 heavy-duty diesel hybrid-electric buses was the subject of the U.S. Department of Energy (DOE)/National Renewable Energy Laboratory (NREL) Transit Bus Evaluation Project.

The hybrid buses were operated from Manhattanville Depot during the evaluation presented in this report. The hybrid buses are compared to 7 NovaBUS diesel buses operating from the same depot as the hybrid test buses and 7 Orion diesel buses operating from a nearby depot.

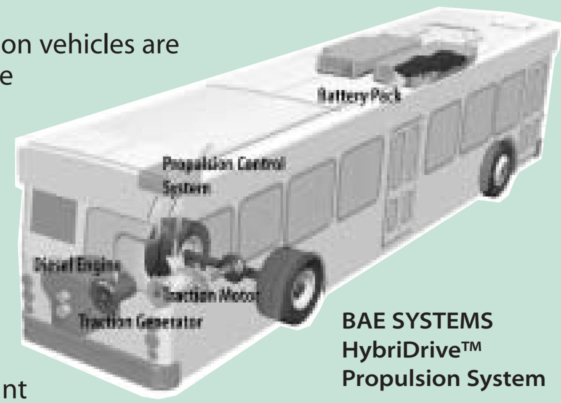
This report summarizes the results of the diesel hybrid-electric study at NYCT. Further technical background, research methods, extensive original data, and detailed discussions are presented in a companion document *(New York City Transit Diesel Hybrid-Electric Bus Site Final Data Report, NREL*, February 2002), which is available from the National Alternative Fuels Hotline (1-800-423-1363) and on the Web (www.afdc.doe.gov).

What Is a Hybrid Propulsion System?

A hybrid-electric vehicle (HEV) combines an electric propulsion system (electric motor or motors driving the wheels) with another power plant such as a conventional internal combustion engine in order to use the advantages of each.

The series hybrid vehicles at NYCT have a smaller-than-standard diesel transit bus engine, which uses ultra-low sulfur fuel. The diesel engine operates within a narrow speed range, so it uses less fuel.

In general, electric propulsion vehicles are valued because they reduce mobile vehicle emissions. However, all-electric vehicles usually are limited by range and onboard energy storage. The use of a power plant in the HEV allows an extended range compared with all-electric vehicles. In a transit bus, the power plant is usually an internal combustion engine that is smaller than a standard transit diesel engine.



BAE SYSTEMS HybriDrive™ Propulsion System

The hybrid system evaluated at NYCT works in general as follows:

1. The diesel engine powers a traction generator that provides primary power through the propulsion control system to the traction motor and recharges the batteries. The range of the bus is limited by the amount of diesel fuel stored onboard, not by a need to recharge the batteries.
2. The traction motor drives the wheels and regenerates power during braking.
3. Batteries provide supplemental power to a traction motor during acceleration and grade climbing.
4. The propulsion control system manages the flow of power to make the bus move as the driver commands and uses regenerative braking to slow the bus and simultaneously recharge the batteries. (Hybrid buses also have conventional brakes.)
5. The system is integrated. During acceleration, power flows from the traction generator and battery pack to the traction motor; during cruise mode, power flows from the traction generator to drive the traction motor and recharge the batteries as needed; and during braking, the traction motor acts as a generator, sending power to the batteries for recharging.
6. The smaller diesel engine, operating at a more constant speed and with better overall fuel economy, can significantly reduce overall bus emissions.

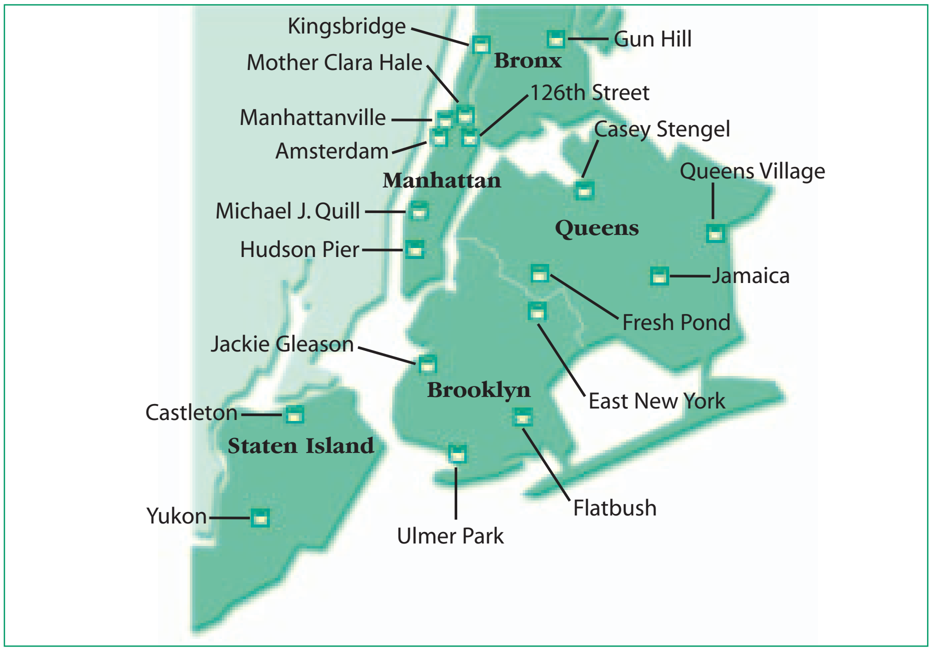


Figure 1. New York City Transit bus depot locations

Alternative Fuel Projects at DOE and NREL

NREL managed the data collection, analysis, and reporting activities for the NYCT Diesel Hybrid-Electric evaluation on behalf of DOE. NREL is a DOE national laboratory. Support was also provided by Battelle.

One of NREL's missions is to assess the performance and economics of alternative fuels and advanced technology propulsion systems objectively so that

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

Besides the advanced diesel hybrid-electric propulsion system, alternative fuels being evaluated by NREL and participating companies across the United States include liquefied natural gas (LNG), compressed natural gas (CNG), biodiesel, ethanol, and propane (liquefied petroleum gas, or LPG).

The Transit Bus Evaluation Project

The overall objective of the ongoing DOE/NREL Transit Bus Evaluation Project is to compare heavy-duty transit buses using alternative fuel or advanced propulsion technology with those using conventional diesel fuel. Specifically, the program seeks to provide comprehensive, unbiased evaluations of the newest generation of fuel, engine, and vehicle technologies.

Heavy-duty alternative fuel buses have been evaluated across the United States through data collection and analysis since1993. The bus program has included 14 demonstration sites (Table 1).

Sites have been selected according to the kind of advanced technology in use, the types of buses and

Table 1. DOE/NREL Transit Bus Evaluation Project Demonstration Sites

Site/Operator	Fuel/Technology
DART (Dallas, TX)	LNG
Pierce Transit (Tacoma, WA)	CNG
Miami MDTA (Miami, FL)	CNG, Methanol
NYCDOT/Triboro Coach (New York, NY)	Methanol
NYCDOT/Command Bus (New York, NY)	CNG (emissions only)
GP Transit (Peoria, IL)	Ethanol
MCTO (Minneapolis, MN)	Ethanol
Bi-State (St. Louis, MO)	Biodiesel
Atlanta, GA and Flint, MI	CNG/Diesel (emissions only)
Long Island, NY and Cincinnati, OH	CNG/Diesel (emissions only)
GO Boulder (Boulder, CO)	CNG
NYCT (New York, NY)	Diesel hybrid-electric

engines, the availability of diesel comparison (“control”) vehicles, and the host site’s interest in using alternative fuels and advanced technology.

The data collection and evaluation efforts are subject to peer review and DOE approval. The results of the evaluation at each site have been published separately and are available from the National Alternative Fuels Hotline (1-800-423-1363) and on the Web at www.afdc.doe.gov.

The objective of this project at NYCT is to provide a reasonable comparison between currently available advanced propulsion technology and standard diesel transit buses. This comparison includes economic, technical, emissions, and safety factors.

Data are collected on the operational, maintenance, performance, and emission characteristics of each alternative fuel or advanced propulsion fleet and comparable diesel fleet operating at the same site. Transit agencies considering the use of advanced propulsion technology buses are the primary intended audience for this information.

Emission Reduction Options for Transit Vehicles

The use of natural gas has been increasing significantly in the transit bus market since 1994 because natural gas engines can have significantly cleaner emissions than standard diesel engines. The major downside with natural gas for transit companies is the extra costs for vehicles, fueling facilities, and maintenance facility upgrades to accommodate the use of natural gas. These investments are substantial.

Both propane and electric vehicles have been available for smaller than full-size transit buses. All-electric vehicles have an issue of reduced range compared to conventional diesel vehicles of a similar size.

Hybrid-electric buses are expected to allow the use of cleaner electric power, require a smaller engine or power plant compared to a standard vehicle, and extend the range of an all-electric vehicle by use of the power plant and regenerative braking. The challenge with hybrid-electric vehicles is the complexity of using electric motors, energy storage devices such as batteries, a power plant such as a small diesel engine, and regenerative braking all in one vehicle.

One purpose of the DOE/NREL Transit Bus Evaluation is to determine the commercial potential, cost, emission reduction benefits, technical hurdles, and economic challenges affecting the adoption of advanced technology buses.

Host Site Profile: NYCT

The MTA, of which NYCT is the largest agency, had an annual budget of $7.3 billion for 2001 and provides transportation for nearly 7.8 million passengers. The MTA provides rail and bus service in the New York City area, using 4,871 buses and 7,849 passenger rail and subway cars.

The NYCT Department of Buses operates more buses than any other public agency in North America. Its 4,489 buses serve New York City from 18 depots. These buses cover 235 routes, which total 1,871 miles each day. The NYCT bus fleet operates 115 million miles annually and serves an estimated 2.2 million paying customers daily.

Like most other transit companies in the United States, NYCT has been testing clean emission transit buses over the past 10 years. NYCT plans to purchase CNG and diesel hybrid buses, as well as retrofit the entire existing diesel bus fleet with catalyzed diesel particulate filters (DPFs). Lower sulfur content diesel fuel has also been used since 2000.

The overall goal of the NYCT plan includes having 385 diesel hybrid buses and 646 CNG buses in service by 2006. NYCT also plans to have the entire existing diesel bus fleet converted to using catalyzed DPFs in 2004.

NYCT's Diesel Hybrid-Electric Transit Buses

NYCT introduced heavy-duty hybrid technology into its operation in 1998 with one retrofitted NovaBUS RTS bus with a prototype Allison series hybrid system and with four new Orion VI hybrid buses with the Lockheed Martin Control Systems (now BAE SYSTEMS) HybriDrive™ propulsion system. The HybriDrive™ buses were placed into service in September 1998. The NovaBUS RTS hybrid bus from Allison was operated until 1999.

NYCT ordered 10 Orion VI hybrid buses in 1997. The first four Orion VI hybrid buses were originally planned for delivery to New Jersey Transit but were instead purchased by NYCT. The fifth Orion VI hybrid bus started service in March 1999. The other five Orion VI vehicles were placed into service in mid-2000. In general, NYCT considered this fleet of 10 Orion VI hybrid buses to be a test (or pilot) fleet. These buses are considered by NYCT and the manufacturers (Orion and BAE SYSTEMS) to be prototypes. As shown in Table 2, the 1998 and 1999 model hybrid buses were compared with 14 conventional diesel transit buses.

Table 2. Vehicle System Descriptions

Comparison Items	Low-Floor Hybrid	High-Floor Diesel (Orion)	High-Floor Diesel (Nova)
Operating Facility (Depot)	Manhattanville	Amsterdam	Manhattanville
Number of Buses	10	7	7
Chassis Manufacturer/Model	Orion VI	Orion V	NovaBUS RTS
Passenger Capacity Based on GVWR	64	75	79
Number of Seats	32	39	40
Free Floor Space* (ft^2)	87	83	73
Chassis Model Year	1998, 1999	1998	1998
Engine Manufacturer/Model	Navistar/DDC S30	DDC S50	DDC S50
Rated Horsepower	230 bhp @ 2300 rpm	275 bhp @ 2100 rpm	275 bhp @ 2100 rpm
Maximum Torque	605 ft-lb @ 1500 rpm	890 ft-lb @ 1200 rpm	890 ft-lb @ 1200 rpm
Compression Ratio	17.5:1	15.0:1	15.0:1
Generator Manufacturer/Model	BAE SYSTEMS	N/A	N/A
Maximum Rating	170 kW @ 2000 rpm	N/A	N/A
Battery Pack Manufacturer/Model	Hawker Sealed Lead Acid	N/A	N/A
Battery Pack	2 roof-mounted tubs, 23 batteries each tub, 580V Total	N/A	N/A
Battery Capacity	64 A-h for each battery at C/3 rating	N/A	N/A
Regenerative Braking	Yes	No	No
Retarder	No	Yes	Yes
Transmission Manufacturer/Model	--	Allison/B-500R	Allison/VR731-RH
Catalyzed DPF Used (Y/N)	Yes (NETT Technologies)	No	No
Fuel System Capacity (gal)	100	150	150
Curb Weight (lb)	31,840	28,500	27,500
Gross Vehicle Weight (GVW)	41,640	39,930	39,500
Bus Purchase Cost ($)	465,000	290,000	290,000

*NYCT standard for scheduling service is 3.7 ft^2 per standee.

The comparison or diesel control buses, all model year 1998, were located at two NYCT depots.

The first 10 hybrid buses cost an average of $465,000 each. A typical diesel bus at NYCT costs about $290,000. For comparison, the next-generation hybrid buses ordered by NYCT had a purchase price of $385,000 each, and a CNG bus purchase price at NYCT is about $320,000. Figure 2 shows the Manhattanville Depot.

NYCT's Involvement in Air Quality Improvement

NYCT is committed to using clean fuel vehicles: it purchased 34 CNG buses in 1995 and added another 190 CNG buses in operation in 2000. In early 2000, New York Governor George Pataki and NYCT completed a clean air plan that provides funding through 2004 to NYCT to purchase CNG and hybrid buses, use ultra low-sulfur diesel fuel (ULSD) for the entire diesel fleet, retrofit diesel buses with catalyzed DPFs, and convert several depots to accommodate CNG buses.Table 3 illustrates NYCT's commitment to hybrid and CNG bus technology.

Project Design and Data Collection

One goal of the DOE/NREL Transit Bus Evaluation Program is to compare advanced technology vehicles with nearly identical diesel "control" vehicles operating in the same duty cycle. The diesel comparison vehicles in this evaluation were in two groups: NovaBUS RTS diesel buses from the Manhattanville Depot and Orion V diesel buses from the Amsterdam Depot. Both of the comparison bus models have some significant differences from the hybrid buses.

The Orion V diesel buses at Amsterdam were chosen to compare to the hybrid buses because the vehicle chassis were built by the same manufacturer in nearly the same model year; however, the duty cycle at Amsterdam was slightly different than the cycle at Manhattanville.

The NovaBUS RTS buses at Manhattanville were chosen to compare to the hybrid buses because the operating duty cycle was essentially the same for both fleets, and they were operated from the same depot; however, the bus chassis is significantly different.

The two diesel study fleets started operations at about the same time in March and April 1999, so their respective ages are similar.

Table 3. **Recent and Planned Hybrid and CNG Bus Purchases by NYCT**

Delivery Year	Number of Buses	
	Hybrid	CNG
As of 1998–2001	10	221
2002	125	125
2003–2004	200	130
2006	50	170
Total	**385**	**646**

PIX 10878

Figure 2. **Manhattanville Depot in New York**

Because of major hardware changes (including a new engine), the first hybrid bus (6350) was removed from the evaluation. Data are included in the report but not in the totals for the hybrid buses.

The nine other hybrid buses have been split in two groups for the evaluation—four of the five older hybrid buses versus the five newer hybrid buses. All of the hybrid buses had the same general specifications, but the split into two subsets for analysis was made to explore the improvements made to the newer buses after the start of testing of the fifth hybrid bus. The older buses are 14–20 months older (based on date placed into service) than the last five hybrid buses in the group. Although the older and newer hybrid buses represent the same Orion VI chassis, they have some differences, as described in the section below on Lessons Learned.

The evaluation period for the fuel and maintenance analyses was chosen to make sure that data were taken for all of the hybrid buses only while they were operating at the Manhattanville Depot.

Data were gathered from NYCT's fuel and maintenance tracking systems daily. Examples of the data parameters included:

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

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

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

The study design included the tracking of safety incidents affecting the vehicles or occurring at NYCT's terminal facilities. However, no reportable safety incidents occurred during the data collection period.

NYCT's Facilities

NYCT operates 246 buses from the Manhattanville Depot in West Harlem (Figure 3) including the 10 Orion diesel hybrid-electric vehicles. The Manhattanville Depot opened for bus operations in November 1992.

The building has four levels and provides 340,000 square feet of working space inside. The first floor houses the diesel fueling station, bus wash, and maintenance area. The fueling lanes are shown in Figure 4. The second and third floors are used to store the buses. The fourth floor contains offices and drivers' rooms, with some outside employee parking. There is a modest outdoor apron on the first floor for moving and storing vehicles outside the building (Figure 2).

The Manhattanville Depot operates three diesel fueling lanes and has 40,000 gallons of diesel fuel stored on site in 10 underground tanks. The bus operation uses approximately 9,000 gallons of diesel fuel per night.

For the hybrid buses, electrical charging stations were added to the third floor. These charging stations were installed as an experiment by the New York Power Authority for providing grid electricity for charging the bus traction batteries. However, the hybrid buses do not require grid connection and were not charged during this evaluation.

Battery conditioning is required on a 6-month basis to extend the

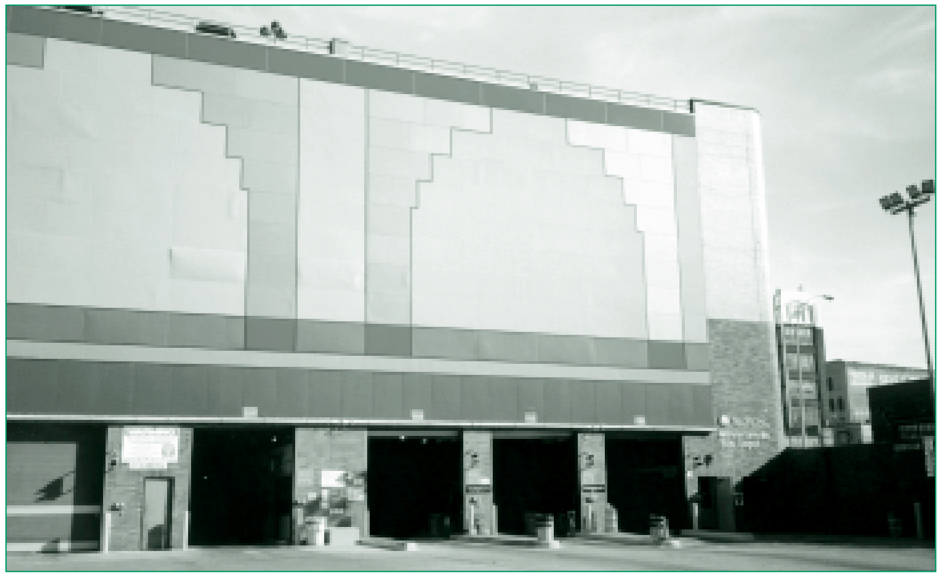

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Figure 3. Manhattanville Depot, New York

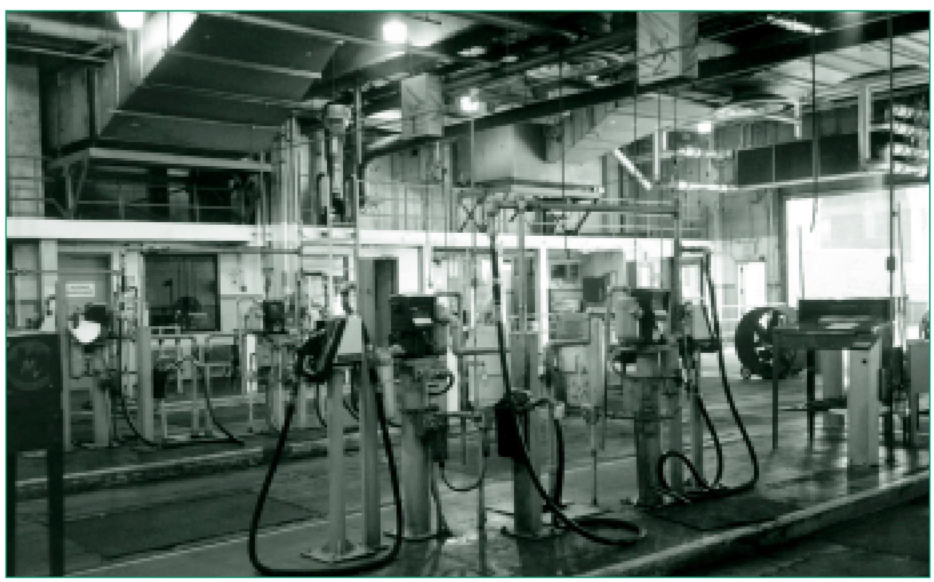
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Figure 4. Diesel fueling lanes at Manhattanville Depot

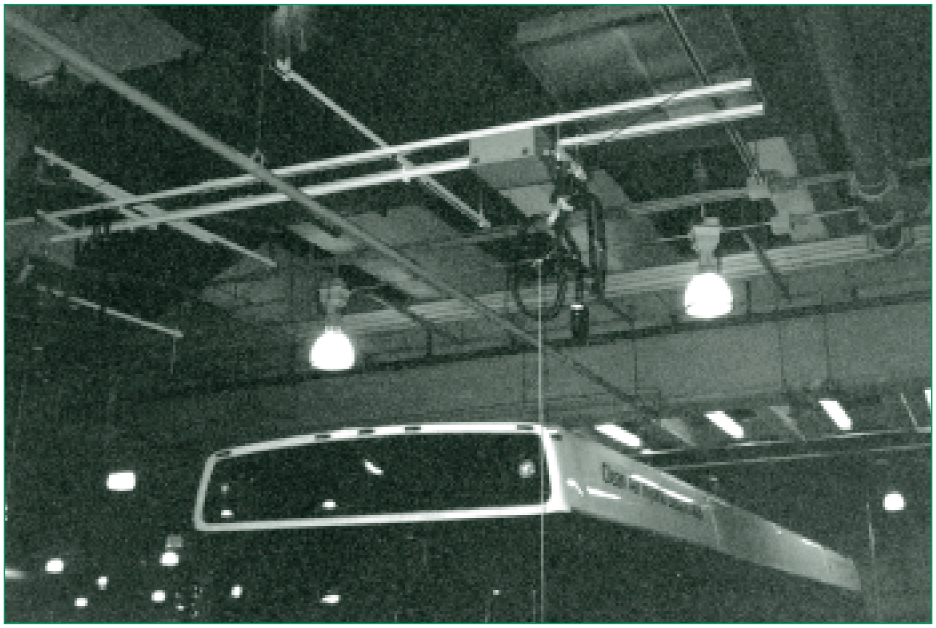
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Figure 5. Ceiling-mounted charging hookup for hybrid bus batteries

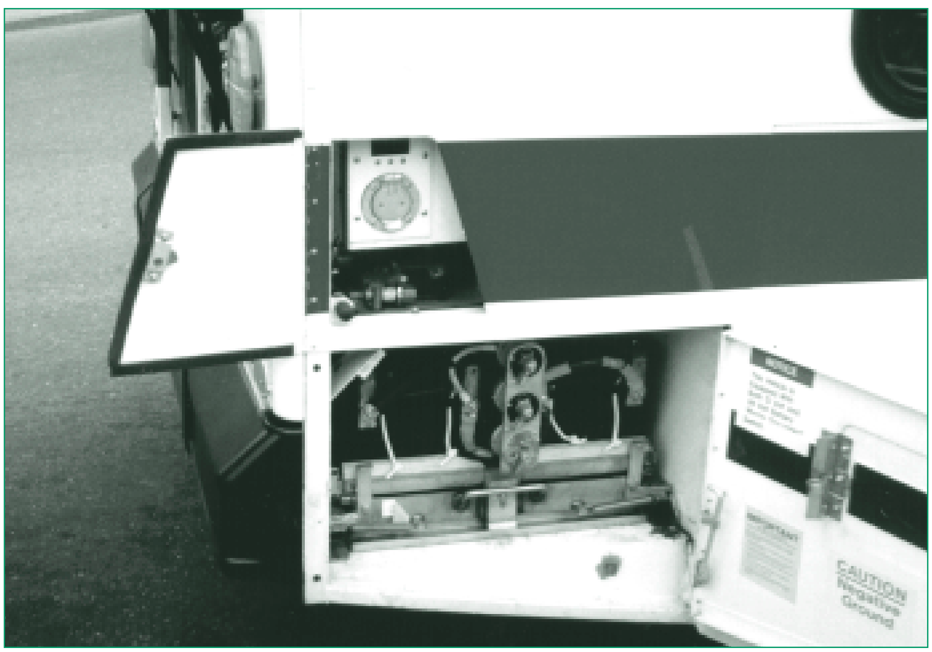

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Figure 6. Rear quarter of hybrid bus showing battery conditioning port (top)

life of the batteries in the hybrid system. Battery conditioning consists of a very slow, controlled overcharging of the battery pack in an attempt to equalize the charge between batteries and clean off the plates within the batteries. It takes 12–24 hours.

Equipment for battery conditioning is installed at the Manhattanville depot on the third floor near the charging stations (Figure 5). Buses are parked near the overhead equipment and then plugged in. Figure 6 shows the battery conditioning port on a hybrid bus.

The depot also had a crane installed above one of the maintenance lanes for easier removal and installation of battery packs on the hybrid buses. Many bus maintenance facilities may already have this type of equipment for servicing the equipment placed on the roofs of low-floor buses because of diminished space for equipment under the floor of the bus. No information on installation, operating, or energy costs for the electrical or crane equipment was available for this evaluation.

There are 763 employees at the Manhattanville Depot, of whom 600 are bus operators and 62 are bus maintainers (mechanics).

Project Start-Up at NYCT

Based on the success of an early prototype hybrid bus project in 1996, NYCT ordered 10 diesel hybrid-electric transit buses, the first of which began operating in 1998. The diesel hybrid-electric buses were built by Orion, with propulsion systems by BAE SYSTEMS (formerly Lockheed Martin). NYCT brought hybrid vehicles into its transit fleet to reduce emissions and increase fuel economy. Also, the cost of the fuel-related infrastructure was lower than that of other alternative fuel systems.

Goals of the Orion VI Diesel Hybrid-Electric Fleet

At the time that the 10 Orion VI hybrid buses were delivered, this was the largest standard 40-foot hybrid bus fleet in the United States. Hybrid buses were not a standard configuration for transit applications. BAE SYSTEMS, Orion, and NYCT set out to design, build, and implement the use of hybrid buses into standard transit service. However, all parties were aware that this was an investment into unproven technology, and this project was intended to develop this technology. NYCT set specific goals for this implementation of hybrid buses in order to measure the success of this development project:

1. Reduce emissions, specifically oxides of nitrogen (NO_x <15 g/mi) and particulate matter (PM <0.06 g/mi)
2. Significantly increase fuel economy
3. Show that the hybrid buses can operate in regular revenue service with no route or driver restrictions
4. Show that the hybrid bus performance (e.g., acceleration, gradability, and range) was equal to or better than that of conventional diesel buses and that drivers can switch from one to the other with no significant difference in operation
5. Demonstrate that drivers and passengers perceive hybrid-electric buses positively
6. Significantly increase brake life
7. Improve the design of the hybrid bus; promote the development of the technology through investment
8. Help put the industry in a position to build and sell “production” hybrid buses.

All indications from the NYCT program and this evaluation show that this implementation of diesel hybrid-electric buses has met or exceeded all goals.

Challenges Encountered during Start-Up

The challenges encountered during introduction of the hybrid vehicles have been similar to those encountered during any new technology introduction: the need to develop new safety procedures and to ensure that personnel are properly trained, a learning curve as mechanics became familiar with new

Lessons Learned at Start-Up*

- A team effort is required to develop a prototype system into a proven, off-the-shelf system.
- Vendor, manufacturer, and in-house management support are critical during the learning curve at the transit depot, as maintenance personnel diagnose, troubleshoot, and adapt to the new systems.
- Operators reported that the hybrid buses had better acceleration, better traction in bad weather, and smooth braking.
- Minimal special training for operators was required.
- The hybrids could be used on all of NYCT's routes.
- Riders noticed the quieter ride, and many expressed interest in the "electric power" system on the buses.
- Some obstacles to the commercial growth of hybrid bus technology include the performance of current lead-acid batteries, the availability of medium-duty engines certified for transit bus applications, and the high purchase cost of the first generation of production vehicles. This high purchase cost is exacerbated by the small size of the transit bus market, which cannot support the development of new technologies on its own.
- The prospects for greater commercial success would be improved by the availability of low cost advanced energy storage devices and lower production costs based on the increased production volume that may result from greater penetration of the truck and military markets.

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

equipment and troubleshooting procedures, and difficulty in identifying and obtaining replacement parts for first-generation pre-production vehicles. These issues were exacerbated by the fact that the hybrid fleet represented only a small fraction of the total fleet at the assigned operating location. In addition, there were a number of premature failures of hybrid system components, including traction batteries, traction motors, and generators. Some of these failures were related to component design, and some were related to the low volume manufacture of these components. All of these issues have been addressed via redesign.

Among other differences, the roof-mounted battery tubs on the hybrid buses require the use of a crane in the maintenance area, and the traction generators, traction motors, and computer control system of the hybrid buses represent new technologies for diesel mechanics to learn.

A number of changes to equipment and software were made in the course of project start-up at NYCT. All of the lessons learned with the Orion VI hybrid buses (see box) have been incorporated into the next-generation (Orion VII) hybrid buses.

Evaluation Results

The analyses in this report cover 9 diesel hybrid-electric transit buses and 14 diesel transit buses operating over focus periods of up to 12 months, as shown in Table 4. The fuel and maintenance data collection periods were chosen to analyze each vehicle over a similar range of accumulated mileage.

Actual Bus Use in Revenue Service

The hybrid buses and the NovaBUS RTS study buses were operated from the Manhattanville Depot, and the Orion V diesel buses were operated from the Amsterdam Depot. The buses at the Manhattanville Depot are operated on 8 Manhattan routes 7 days per week, up to 24 hours per day. The buses at the Amsterdam Depot are operated on 2 Manhattan and 6 Bronx routes 7 days per week, up to 24 hours per day.

Buses are randomly dispatched from each of the two depots. Based on the route assignments

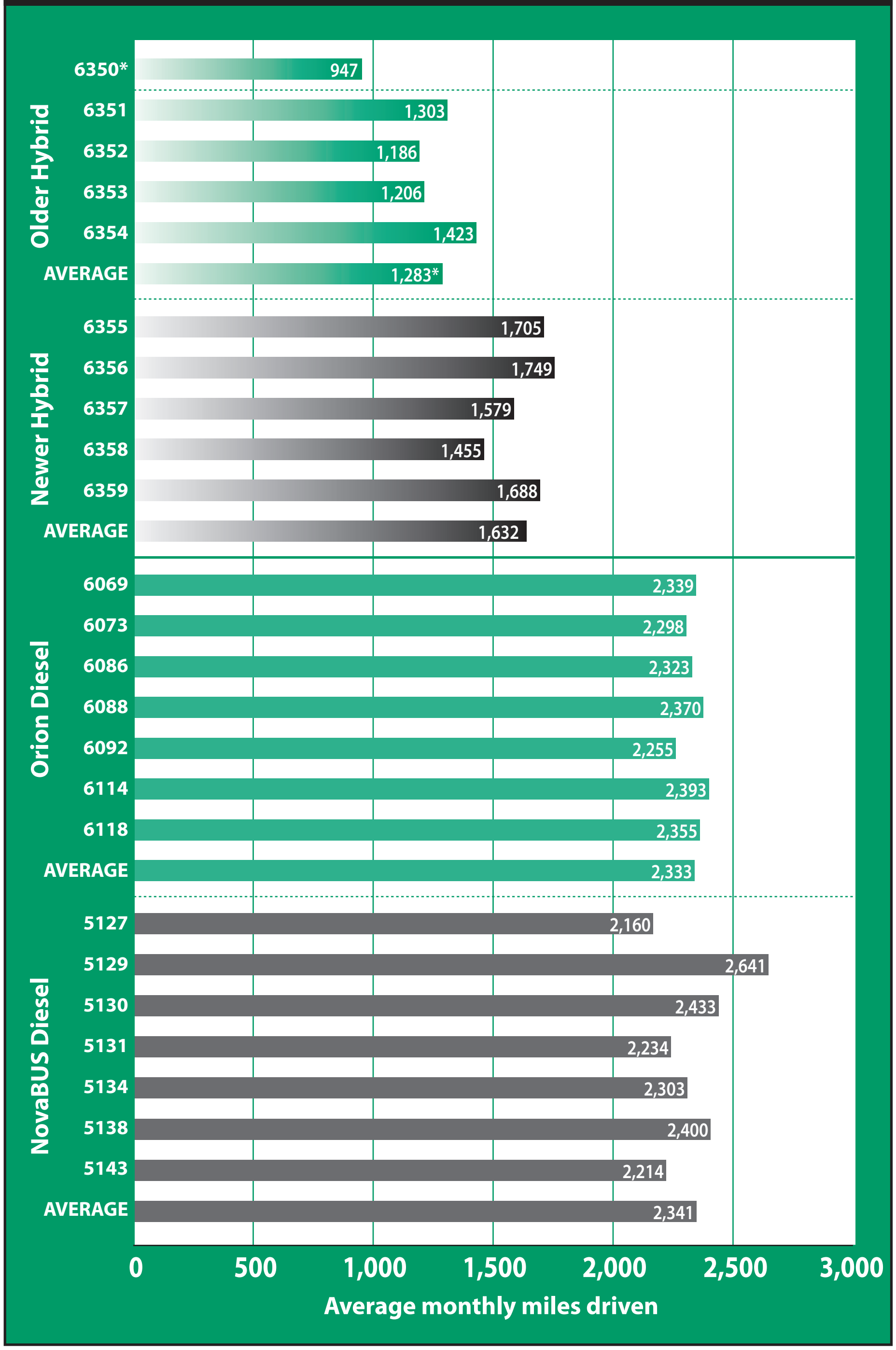
Table 4. Start of Operation Date, Fuel Data Period, and Maintenance Data Period for Each Study Bus

Group	Bus Number	Bus Model	Operating Facility	Start Date of Operation	Fuel Data Period	Maintenance Data Period
	6350**	Orion VI Hybrid	Manhattanville	8/31/98	7/00–9/01	7/1/00–9/30/01
Older Hybrid	6351	Orion VI Hybrid	Manhattanville	9/21/98	7/00–9/01	5/17/2000–7/23/2001
	6352	Orion VI Hybrid	Manhattanville	9/22/98	7/00–9/01	4/26/2000–5/20/2001
	6353	Orion VI Hybrid	Manhattanville	9/22/98	7/00–9/01	4/18/200–7/12/2001
	6354	Orion VI Hybrid	Manhattanville	3/12/99	7/00–7/01*	4/19/2000–6/19/2001
Newer Hybrid	6355	Orion VI Hybrid	Manhattanville	4/19/00	7/00–7/01*	6/20/2000–7/23/2001
	6356	Orion VI Hybrid	Manhattanville	4/21/00	7/00–7/01*	6/8/2000–7/7/2001
	6357	Orion VI Hybrid	Manhattanville	5/12/00	7/00–9/01	7/3/2000–7/26/2001
	6358	Orion VI Hybrid	Manhattanville	5/12/00	7/00–9/01	7/6/2000–8/9/2001
	6359	Orion VI Hybrid	Manhattanville	5/12/00	7/00–9/01	8/2/2000–9/9/2001
Diesel	6069	Orion V Diesel	Amsterdam	5/10/99	7/00–9/01	6/22/1999–6/6/2000
	6073	Orion V Diesel	Amsterdam	3/29/99	7/00–9/01	4/28/1999–4/12/2000
	6086	Orion V Diesel	Amsterdam	4/22/99	7/00–9/01	5/22/1999–5/19/2000
	6088	Orion V Diesel	Amsterdam	4/7/99	7/00–9/01	4/30/1999–5/19/2000
	6092	Orion V Diesel	Amsterdam	4/7/99	7/00–9/01	5/6/1999–5/25/2000
	6114	Orion V Diesel	Amsterdam	5/4/99	7/00–9/01	6/4/1999–6/26/2000
	6118	Orion V Diesel	Amsterdam	5/4/99	7/00–9/01	6/18/1999–6/2/2000
Diesel	5127	NovaBUS RTS	Manhattanville	3/22/99	7/00–9/01	4/15/1999–4/14/2000
	5129	NovaBUS RTS	Manhattanville	3/22/99	7/00–9/01	4/15/1999–3/29/2000
	5130	NovaBUS RTS	Manhattanville	3/22/99	7/00–9/01	4/23/1999–4/22/2000
	5131	NovaBUS RTS	Manhattanville	3/22/99	7/00–9/01	4/18/1999–3/25/2000
	5134	NovaBUS RTS	Manhattanville	3/22/99	7/00–9/01	4/14/1999–4/10/2000
	5138	NovaBUS RTS	Manhattanville	3/22/99	7/00–9/01	4/17/1999–4/1/2000
	5143	NovaBUS RTS	Manhattanville	3/22/99	7/00–9/01	4/20/1999–4/10/2000

* These three hybrid buses were moved to Mother Clara Hale Depot at the end of July 2001 for operation. The data from operation of these vehicles at this new depot have not been included in any of the analyses provided in this report.

** Hybrid bus 6350 was not included in the evaluation because of the repower of the engine.

Figure 7. Average miles driven per month, by bus and fleet



*Mileage for 6350 is not included in the average due to the repower of the engine. Older Hybrid group includes 6351-6354; Newer Hybrid group includes 6355-6359.

and daily assignment of buses from each depot for operating year 2000, the average speed for buses from Manhattanville was 6.43 mph, compared with a speed of 5.90 mph for buses from Amsterdam. These values were averaged over an entire week of operation.

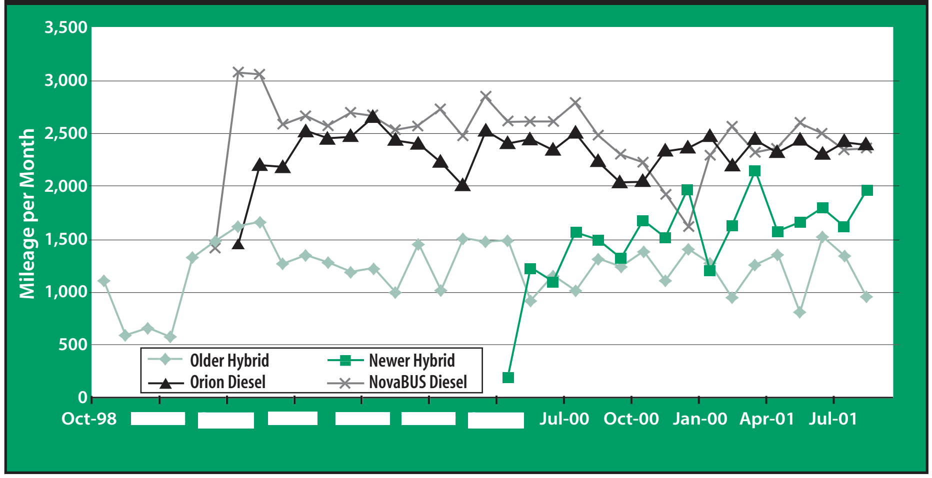
The buses operating from Amsterdam have an 8% lower average speed, which indicates that the fuel economy should be expected to be slightly lower for the buses operating from the Amsterdam Depot when compared to those operating from the Manhattanville Depot.

Figure 7 shows the average monthly mileage for each vehicle and fleet. Figure 8 shows the fleet average monthly mileage over time. The two diesel fleets had essentially the same average mileage. The older group of hybrid buses had an average mileage 45% lower than the diesel buses at Manhattanville (NovaBUS). The newer group of hybrid buses had an average mileage only 30% lower than the same diesel buses at Manhattanville.

The lower average mileage of the hybrid buses is an indicator of how much the hybrid buses were out of service for maintenance and upgrade issues. The newer hybrid bus group had a few months where their usage was nearly to the level of the diesel bus usage (December 2000 and March 2001), which indicates significant improvement in availability for service.

Fuel consumption records indicate that when the hybrid buses were operated, they were used in nearly the same service as the diesel buses at Manhattanville because the average daily mileage was nearly the same. The hybrid buses had lower usage based on the need for more maintenance and downtime for servicing and parts supply; however, when the hybrid buses were in service, they were used at nearly the same level as the diesel buses at Manhattanville.

Figure 8. Average monthly mileage per fleet, over time



Fuel Economy and Maintenance Costs

The diesel hybrid-electric buses had greater fuel economy than the diesel buses, but maintenance costs for the hybrid buses were significantly higher. The maintenance cost differences were most likely attributable to the novelty of the hybrid propulsion system at the Manhattanville Depot and the difficulty in obtaining replacement parts for an unfamiliar bus system.

Once a new generation of hybrid buses is deployed in greater numbers, the costs for troubleshooting and repair should decline.

Fuel Economy

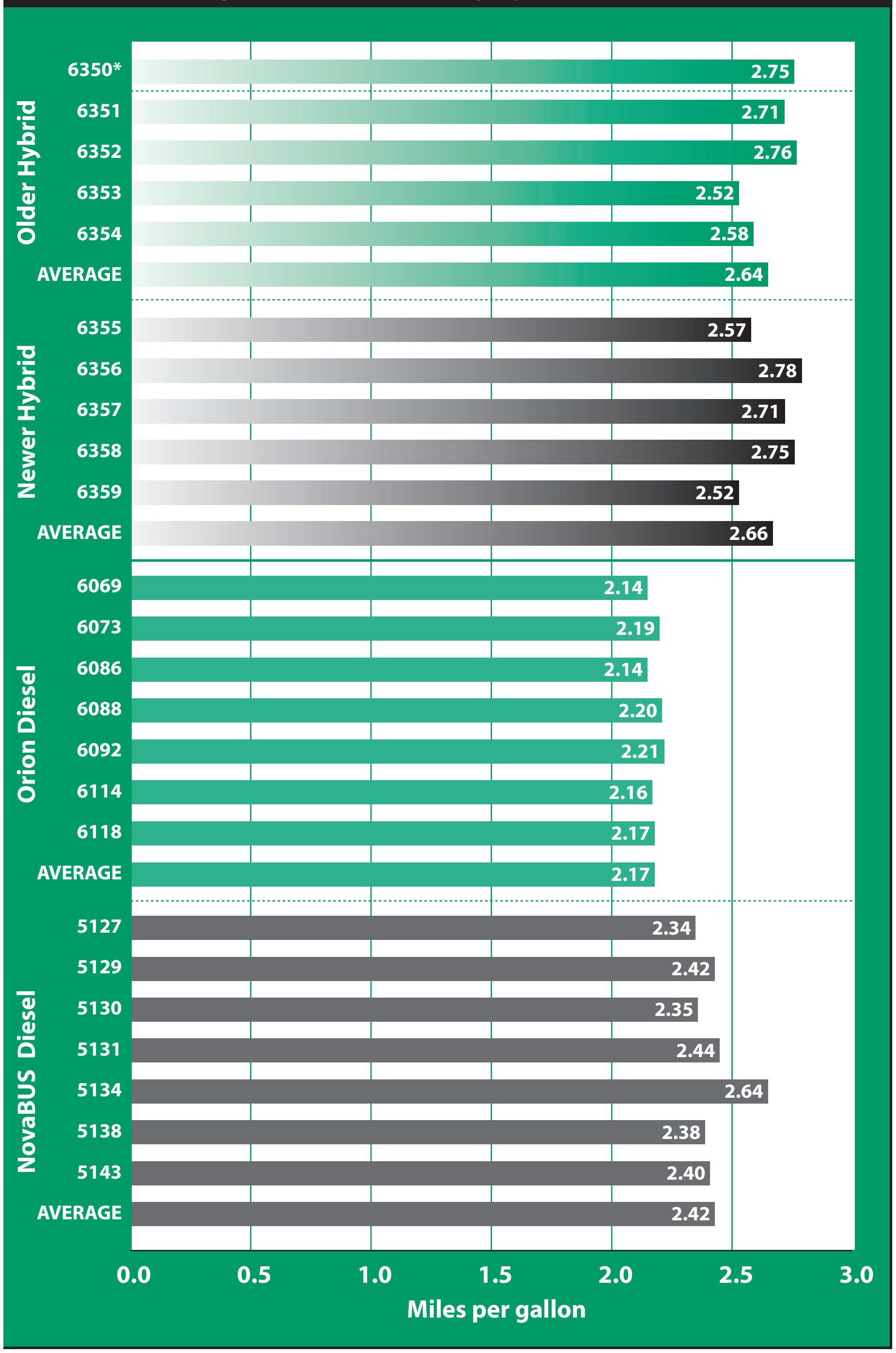
NYCT uses Jet A diesel fuel, which is designated as aircraft fuel. NYCT and the other transit bus operators in the area use Jet A diesel fuel because of its availability in the city. This fuel designation is a slightly higher grade than diesel #1. NYCT uses ULSD fuel at less than 30 ppm sulfur content for its Jet A diesel fuel.

Fuel consumption and economy are shown for the study groups on a per-bus and per-fleet basis in Figure 9 for the evaluation period. Also, during the evaluation period, NYCT was not performing any external charging of the traction batteries from the electric grid; therefore, essentially all energy consumed by hybrid buses came from the diesel fuel consumed by the engine.

The two hybrid bus groups had essentially the same fuel economy at an average of 2.65 mpg, which is higher than the average fuel economy of the diesel buses. The diesel buses at Manhattanville (NovaBUS) had an average fuel economy of 2.42 mpg, and the hybrid bus fuel economy was 10% higher. The diesel buses at Amsterdam (Orion) had an average fuel economy of 2.17 mpg, and the hybrid bus fuel economy was 22% higher.

As mentioned earlier, the duty cycle for the diesel buses at Amsterdam was slightly more difficult than at Manhattanville, which was expected to make the fuel economy significantly lower. The average operating speed from the Amsterdam Depot was 8% lower, and the diesel buses had 10% lower fuel economy than the diesel buses at Manhattanville Depot.

Figure 9. Fuel economy by bus and fleet



*6350 not included in average or total; bus was repowered with a different engine than the other nine hybrid buses.

Figure 10 shows the average fleet fuel economies for each of the study fleets from the beginning of operation. The diesel buses at Amsterdam had the lowest fuel economy. The diesel buses at Manhattanville and the hybrid buses had similar fuel economies until about July 2000. After July 2000, the hybrid buses had higher fuel economy than the diesel buses at Manhattanville.

Larger fuel economy differences between the hybrid and diesel buses were observed during the cooler months, with smaller differences observed during warmer months. This reduction in fuel economy for the hybrid buses may be caused by air conditioning loads and/or thermal "foldback" of the hybrid traction battery operation in the prototype buses.

If the batteries are too hot, the hybrid control system reduces power to help the hybrid system recover and cool the batteries. During this thermal foldback operation, the hybrid system would not be operating optimally. Specifically, the regenerative braking would not be in operation, only the service brakes. Not using the regenerative braking would reduce the fuel economy significantly. Based on specific changes in design to improve battery pack thermal management, BAE SYSTEMS reports that this situation should not occur with the newer Orion VII hybrid bus design. In addition, the Orion VII hybrid will incorporate additional changes to the system that controls regenerative braking that should increase the total amount of regenerative energy that can be effectively captured. The result should be an increase in fuel efficiency and more consistent fuel efficiency throughout the year.

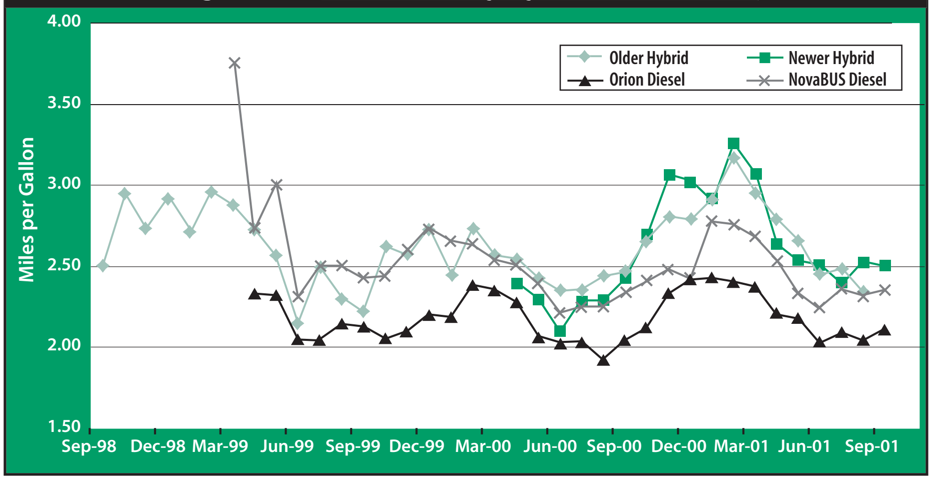
Fuel economy measurements taken during emissions testing on the West Virginia University (WVU) chassis dynamometer showed fuel economy to be 23% greater for the hybrid buses on the Commercial Business District (CBD) controlled test cycle, compared to diesel buses. When tested without regenerative braking, the hybrid's fuel economy during the CBD cycle was still 6% higher for the hybrid buses compared to the NovaBUS RTS diesel bus.

The NY Bus and Manhattan testing cycle fuel economy results were 64% higher and 48% higher, respectively, for the hybrid buses. The results from these emission tests should be considered the maximum results for the hybrid buses because the air conditioning and heating were not used during the testing, and the operation of the hybrid propulsion system was monitored to ensure that thermal foldback did not occur during the testing.

Fuel Costs

The ULSD fuel at NYCT cost an average of $1.03 per gallon during the evaluation. For the evaluation period, the diesel buses at Amsterdam had a fuel cost of $0.474 per mile, the diesel buses at Manhattanville had a fuel cost of $0.426 per mile, and the hybrids had the lowest cost at $0.390 per mile for the older hybrid group (8% lower than the fuel cost for the NovaBUS RTS diesel buses) and $0.387 per mile for the newer hybrid group (9% lower than the fuel cost for the NovaBUS RTS diesel buses).

Figure 10. Fuel economy by month and fleet



Engine Oil Consumption and Cost

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

The engine oil consumption for the Series 30D engine used in the hybrid buses was tracked for the evaluation period. The overall oil consumption was 2.22 quarts per 1,000 miles or 451 miles per quart of engine oil. The cost per quart of engine oil for the buses was $0.64.

The engine oil consumption data for the diesel buses in the evaluation were not complete; therefore no results were available for comparison. The usual engine oil consumption of the Series 50 diesel engine in NYCT service was expected to be 1.5 to 2.0 quarts per 1,000 miles based on discussions with the engine manufacturer.

Factors Affecting Maintenance Costs

Maintenance data were collected from NYCT for each bus back to the start of operation. All maintenance work orders and parts information available have been collected for the study buses.

In this maintenance cost discussion, all work orders marked as accidents have been removed. In general, accidents are random as far as which buses have accidents and how much those accidents cost to repair. Accident repair costs included mostly exterior body damage repair.

For all maintenance cost comparisons, the NovaBUS RTS diesel buses at Manhattanville are used as the baseline. Also, the NovaBUS RTS diesel buses have a duty cycle similar to that of the hybrid buses.

In general, the hybrid buses have higher maintenance costs than the diesel buses in all categories. This has been essentially caused by three main issues: (1) The hybrid buses evaluated in this report are prototype technology; (2) During the evaluation, the depot mechanics were inexperienced with the Orion bus platform, DDC Series 30 engine, and hybrid propulsion systems; and (3) The hybrid buses were a small fleet in a large standard NovaBUS diesel bus fleet (236 of 246 buses at the depot were manufactured by NovaBUS). Maintenance costs are expected to decline significantly when hybrid buses constitute a greater share of the transit fleet at a given depot.

The low number of hybrid buses caused more troubleshooting hours for the mechanics for the buses and the propulsion systems on the hybrid buses because of being unfamiliar with the bus and propulsion system. Also, the mechanics required more time to specify and receive parts for the hybrid buses because of the lack of support for and familiarity with Orion buses at this depot, in addition to difficulty on the part of the manufacturer in providing timely parts support for these pre-production vehicles. This is consistent with the significantly higher labor hours required for the hybrid buses compared to the diesel buses at the same depot.

The hybrid buses have been split into two groups for this evaluation —older and newer hybrid buses. The older hybrid bus group consists of buses 6351 through 6354 and includes 3 of the first 4 buses delivered to NYCT and the pilot bus for this order. Each of these buses is 14–20 months older than the last 5 buses in the 10-bus order. Bus 6350 has not been included in these analyses because the engine was replaced with a Cummins ISB diesel engine in order to gain experience with that configuration for the next order of hybrid buses. The newer hybrid bus group consists of buses 6355 through 6359. These 5 buses all went into service within a 2-month period in April-May 2000. This division is intended to show the significant progress made in the development of this hybrid technology between the earlier and the later delivery within the evaluation data period.

Maintenance Costs by Vehicle System

Figure 11 shows the major system groupings used for the maintenance cost analysis. Across all fleets, cab, body, and accessories and engine/fuel-related maintenance were the highest rated cost categories. Brakes, HVAC (heating, ventilating, and air conditioning), and preventive maintenance inspections also appeared among the top cost categories in one or more fleets.

The following discussion of maintenance by vehicle system focuses on the same 12-month evaluation period shown in Figure 11. The following discussion shows differences in maintenance costs. Unless otherwise indicated, the NovaBUS RTS diesel fleet at Manhattanville is taken as the baseline fleet.

- **Total Engine- and Fuel-Related Systems –** The two diesel fleets are similar, with the Orion diesel fleet having 4% lower costs. The hybrid groups had much higher costs than the NovaBUS fleet (6.8 times higher for the older hybrid and 4.6 times higher for the newer hybrid).

  Exhaust System – The exhaust system maintenance costs for the Orion diesel fleet were very low. The NovaBUS diesel fleet had significant exhaust system repair costs, and the hybrid fleet had the highest costs at 30% higher for the older group and 2.8 times higher for the newer group. The hybrid bus group had catalyzed DPFs installed, and neither diesel fleet had DPFs.

  Fuel System – The repair costs for the Orion diesel fleet were very low. The older hybrid group had costs 19.7 times higher and the newer hybrid group had costs 10.8 times higher than the NovaBUS fleet.

  Engine System – The Orion diesel buses had the lowest repair cost at 34% lower than the NovaBUS diesel fleet. The hybrid buses were again the highest at 4.8 times higher for the older group and 4.1 times higher for the newer group.

  Electric Motor, Generator, and Battery Repairs – Only the hybrid buses have these systems. The costs for these systems were significant at \$0.241 per mile for the older group and \$0.080 per mile for the newer group. The newer hybrid group showed significant improvement in this category.

  Non-Lighting Electrical Systems – The NovaBUS diesel fleet had the lowest costs. The Orion diesel fleet had costs 12% higher, and the hybrid bus groups had costs 2.8 times higher for the older and 2.4 times higher for the newer.

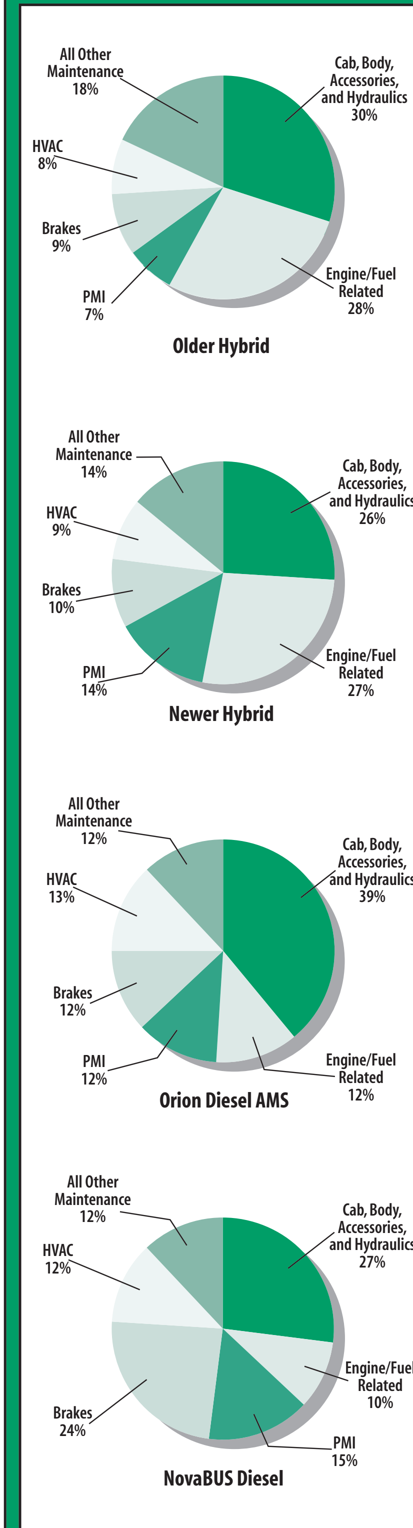
  Air Intake System – The Orion diesel buses had the lowest repair cost at 96% lower. The newer hybrid group had the highest costs at 2 times higher and the older hybrid group had costs 41% lower than the NovaBUS diesel buses.

  Cooling System – The two diesel fleets had about the same cost for this system. The hybrid groups had significantly higher costs at 3.6 times higher for the older hybrids and 5.7 times higher for the newer hybrids.

  Transmission System – The hybrid buses do not have transmissions. The Orion diesel buses had repair costs 32% higher than the NovaBUS diesel buses.

- **Cab, Body, and Accessories Systems –** The hybrid groups had the highest costs at 2.6 times

Figure 11. Share of maintenance costs across major systems



higher for the older group and 65% higher for the newer group. The Orion diesel buses had costs 9% lower than the NovaBUS diesel fleet.

- **Frame, Steering, and Suspension System –** Both of the diesel fleets had similar costs. The hybrid groups had the highest costs at 3.5 times higher for the older hybrids and 2.2 times higher for the newer hybrids.
- **Axle, Wheel, and Drive Shaft Systems –** The two diesel fleets had low costs that were nearly the same. The hybrid groups had costs 4.9 times higher for the older hybrids and 2 times higher for the newer hybrids.
- **Brake System –** The NovaBUS fleet had the highest cost for the brakes. The Orion diesel fleet had costs 62% lower, and the hybrid groups had costs 11% lower for the older hybrids and 27% lower for the newer hybrids. However, one brake reline for bus 6359 has not been included in the analysis. The costs for the brake reline, which were removed from this analysis, were 60 labor hours and $8,339 in parts. The costs for this reline are much higher than expected and have not been fully investigated.
- **Tire Systems –** Tire costs were low because the actual cost of the tires is not included in this maintenance analysis. Only the repair labor hours and a few miscellaneous parts related to the tires have been included here. The older hybrid group had the highest cost at 2.3 times higher and the newer hybrid group had 41% higher costs. The Orion diesel fleet had costs 80% lower.
- **HVAC Systems –** The two diesel fleets had similar costs. The hybrid groups had costs 75% higher for the older hybrid group and 45% higher for the newer hybrid group.
- **PMA Inspections –** PMA inspections only include labor hours for inspections. The costs for the Orion diesel fleet were 37% lower. The older hybrid group costs were 15% higher. The newer hybrid group had higher inspection cost at 57% higher, which may have been caused by an accelerated PMA schedule for four of the hybrids, whose hubodometers were found to be reading out in kilometers instead of miles for part of the evaluation period.
- **Lighting System –** The Orion diesel fleet had costs 78% higher, and the hybrid groups had costs 3.4 times higher for the older hybrids and 2.2 times higher for the newer hybrids.

Warranty Costs

All costs for repairs under warranty have been removed from analyses shown in this report. Warranty costs are not included in the cost analyses because warranty exposure for the manufacturers has usually been included in the initial purchase price of the vehicle. Including warranty costs in the analyses here would be potentially counting those costs twice. Warranty repair information, however, was collected to investigate long-term reliability problems with the vehicles; in other words, to answer the question, “Will this problem continue beyond the warranty period?”

Many warranty issues with the hybrid buses caused configuration changes in the bus systems and significant repair costs. Most of the parts and repair costs have not been included in the maintenance system at NYCT or in this report. Major changes to the hybrid buses include the following:

- Traction batteries and trays
- Power controller cards
- Traction motors
- Traction motor coolant and monitoring
- Catalyzed DPFs
- Traction generator and coupling
- Engine and control system computer software upgrades.

Many other optimization problems were addressed, including repairs to the interlock, doors, brakes (including ABS), suspension hunting issues, air conditioning, and belts for accessories. Each of the hybrid buses appeared to have its own specific problems at start-up that were similar to other hybrid buses. This made troubleshooting and long-term optimization difficult.

Roadcalls

A roadcall is defined in this report as an on-road failure of an in-service bus that requires the bus be taken out of service or replaced on route. Roadcalls are direct indicators of reliability for transit buses. Figure 12 shows distance between roadcalls for the study fleets for all data. Figure 13 shows the same data period for only the roadcalls that involve the engine- and fuel-related systems, which include the non-lighting electrical, air intake, cooling, exhaust, fuel, engine, electrical motors and traction batteries, and transmission. Note that the scales for Figures 12 and 13 are significantly different.

The top three causes of roadcalls for each study fleet are shown in Table 5. For all data, the Orion fleet had a mileage between roadcalls (MBRC) 38% better than the NovaBUS diesel buses for all roadcalls and 42% better for the engine- and fuel-related roadcalls.

Figure 12. Miles between roadcalls for all bus systems

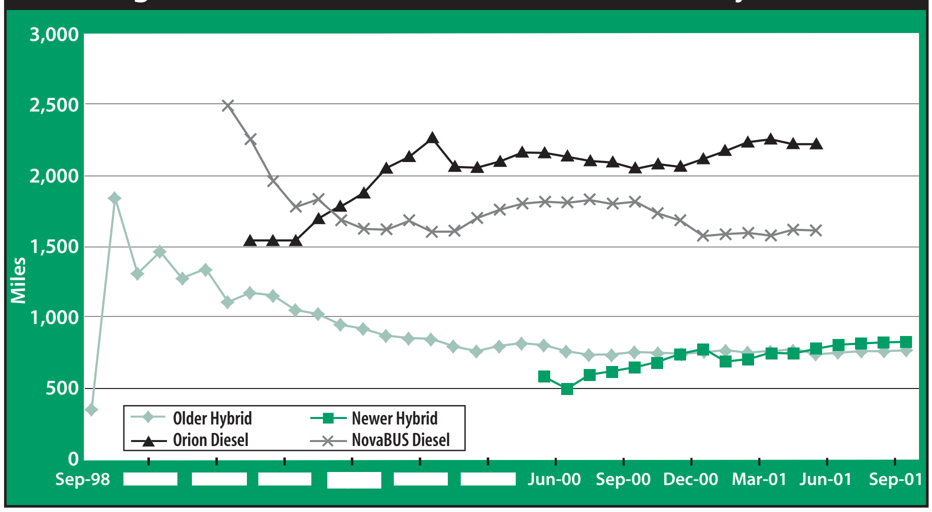


Figure 13. Miles between roadcalls for engine- and fuel-related bus systems

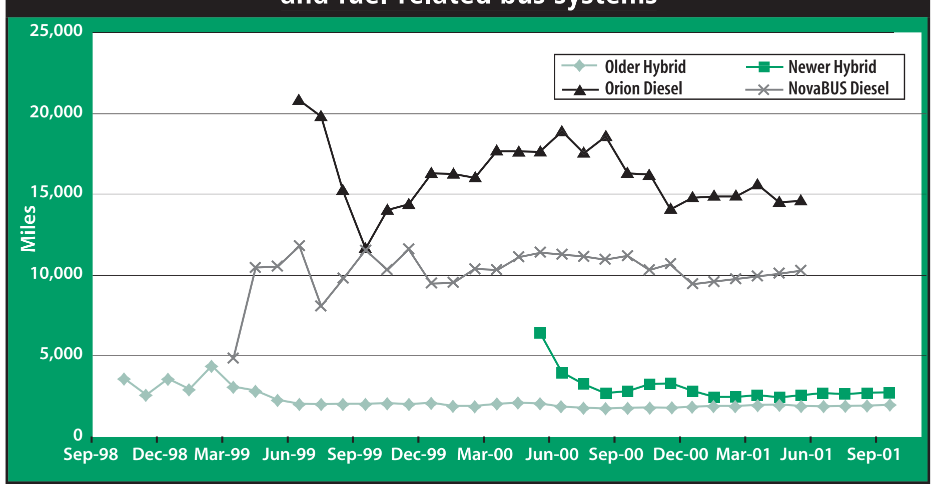
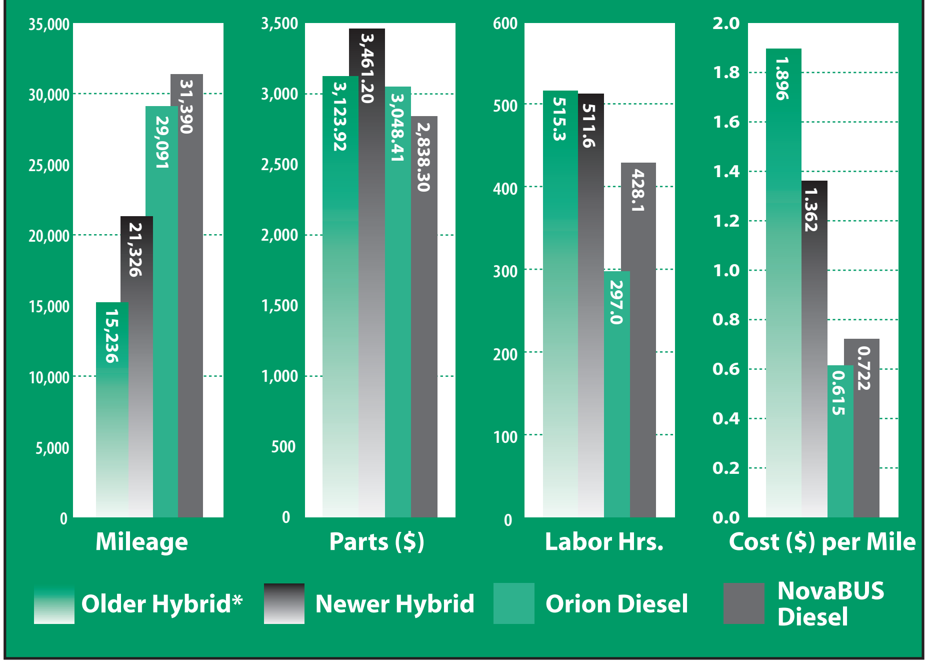


Table 5. Top three causes of roadcalls (in order)

Older Hybrid	Newer Hybrid	Orion Diesel	NovaBUS Diesel
Electric Propulsion	Electric Propulsion	Body Exterior/ Accidents	Door and Interlock
Door and Interlock	Door and Interlock	Wheelchair Lift	Brakes
Engine	Body Exterior/ Accidents	Door and Interlock	Body Exterior/ Accidents

Figure 14. Average maintenance cost per bus, based on mileage (evaluation period)



Labor rate used for calculations was $50 per hour. Cost per mile calculation is (Part Cost + (Labor Hrs x 50))/ Mileage.
* Bus 6350 is not included in the total rows for the hybrids.

The older hybrid buses had an MBRC 52% lower than the NovaBUS diesel buses for all roadcalls and 81% lower for the engine- and fuel-related roadcalls. The newer hybrid buses had an MBRC 49% lower than the NovaBUS diesel buses for all roadcalls and 74% lower for the engine- and fuel-related roadcalls.

For the evaluation period, the Orion fleet had an MBRC 27% better than the NovaBUS diesel buses for all roadcalls and 50% better for the engine- and fuel-related roadcalls.

The older hybrid buses had an MBRC 59% lower than the NovaBUS diesel buses for all roadcalls and 85% lower for the engine- and fuel-related roadcalls. The newer hybrid buses had an MBRC 50% lower than the NovaBUS diesel buses for all roadcalls and 76% lower for the engine- and fuel-related roadcalls.

Overall Maintenance Costs

Figure 14 shows the total maintenance cost per bus, based on mileage, for the evaluation period.

For the evaluation period, the Orion diesel buses from Amsterdam had results compared to the NovaBUS diesel buses as follows: mileage 7% lower, parts costs 7% higher, labor hours 31% lower, and cost per mile 20% lower.

Compared to the NovaBUS maintenance costs, the older hybrid fleet had average mileage 51% lower, parts costs 10% higher, labor hours 20% higher, and cost per mile 146% higher. The newer hybrid fleet had average mileage 32% lower, parts costs 22% higher, labor hours 20% higher, and cost per mile 76% higher.

These results for the hybrid bus groups show the progress made between the older hybrid buses and the newer hybrid buses in reliability and availability/usage. The newer hybrid buses have been used in service much more than the older hybrid buses, and the fleet average cost difference per mile, in comparison with the NovaBUS diesel buses, has been cut almost in half.

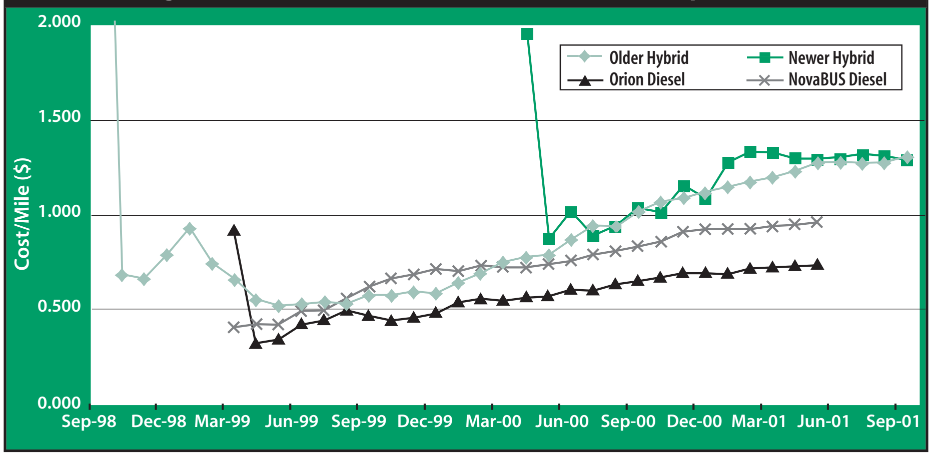
The hybrid bus maintenance costs are significantly higher than those of the NovaBUS fleet. The hybrid fleet required significantly more labor to troubleshoot and repair for nearly all systems on the buses; however, many of the systems with higher costs were unrelated to the hybrid propulsion system.

Many of the repairs for the hybrid buses required significantly more mechanic labor due to extra troubleshooting and more work in looking for and securing replacement parts. Some hybrid bus systems with significant repair costs were the interlock system (which ensures that the bus cannot move when the doors are open), air conditioning (motors), suspension, exhaust, brakes, windshield wipers, wheelchair ramp, doors, and the hybrid propulsion system.

Figure 15 shows accumulated repair costs from the beginning of operation through May 2001 for the two diesel fleets and through September 2001 for the hybrid groups. By accumulating the repair costs, the average cost per mile becomes more and more a trend line from left to right.

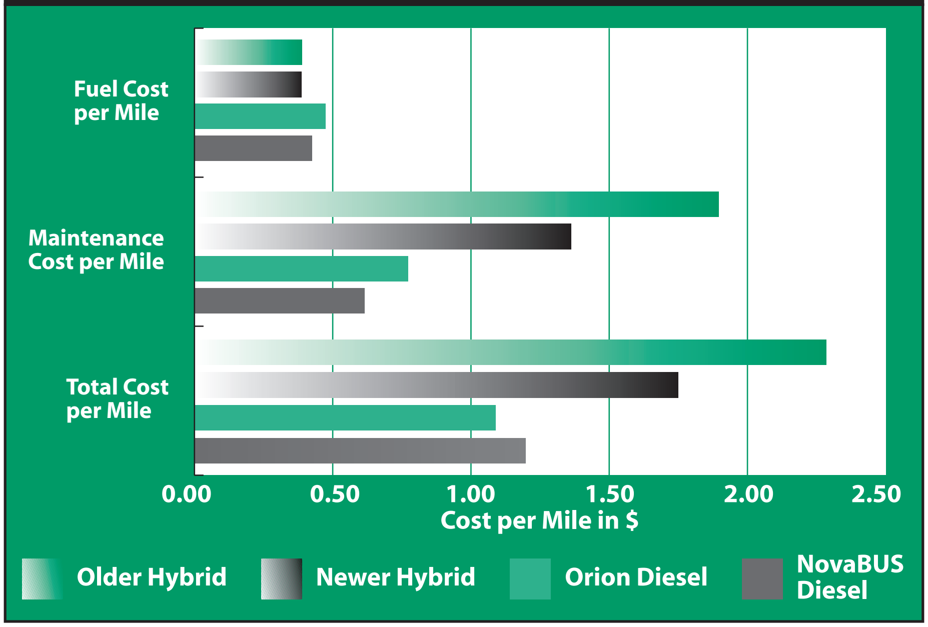
The two diesel fleets have different total maintenance costs because of different maintenance practices and data recording practices between Amsterdam and Manhattanville depots, as well as significant brake problems for the NovaBUS diesel buses at Manhattanville compared to the Orion buses at Amsterdam. However, the upward slopes are nearly the same on the right-hand side of the chart, indicating that the maintenance costs increasing with age are about the same for the two diesel fleets, as would be expected.

Figure 15. Cumulative maintenance costs per mile



The hybrid fleet groups, on the other hand, have a significantly higher/steeper slope upward early in the period, after which the slope levels off. The chart shows that the hybrid maintenance costs were high at the beginning, but were resolved, and the maintenance costs came down to about the same level as the diesel buses. Starting in about January 2000, the hybrid maintenance costs began to climb at a higher rate than those of the two diesel fleets. Based on a review of the maintenance data for the hybrid buses, the major contributors to this increasing maintenance cost are as follows:

Figure 16. Overall operating costs (evaluation period)



- Cab and body (highest contributors: doors, interlock, exterior damage, mirrors, and sun visor)
- Accessories (highest contributor: wheelchair and electrical accessories)
- Electric drive and control
- Engine
- HVAC.

Manhattanville Depot personnel reported that they were taking over more troubleshooting and repair activities on the hybrid buses during 2001 from the manufacturers (Orion and BAE SYSTEMS). Previously, the manufacturers were responsible for nearly all major troubleshooting and repairs of the hybrid buses, even if the hybrid buses were out of service for several days.

Overall Operating Costs

Figure 16 shows a summary of operating costs (without driver labor) based on vehicle mileage. The two diesel fleets have average results that are about the same, with the Orion diesel buses from Amsterdam being 9% lower than the NovaBUS diesel buses from Manhattanville.

The older hybrid buses are much more expensive to operate because of the higher maintenance costs at 92% higher. The newer hybrid buses are also more expensive to operate because of the higher maintenance costs at 46% higher. The newer hybrid buses have cut the operating cost difference in half compared to the older hybrid buses.

Emission Testing Results

There are two main reasons for using hybrid electric buses: (1) potential emissions reductions, and (2) potential fuel economy increases. Although standard diesel transit bus engines continue to meet current emissions certification standards, there continues to be a desire by regulatory agencies such as the U.S. Environmental Protection Agency and the California Air Resources Board to reduce transit bus (and truck) emissions well below levels possible with current diesel technology.

Several clean propulsion technologies have been evaluated for transit bus service in the past 10 years, including the use of methanol, ethanol, natural gas, propane, electric, fuel cells, and hybrid electrics. In general, the only clean propulsion technologies that have been available from an original equipment manufacturer up to about 2001 have been for natural gas, propane, and electric. Starting in 2000, heavy-duty hybrid electric transit buses have become available in numbers larger than one or two demonstration vehicles from Orion and BAE SYSTEMS.

Emission testing performed on the hybrid-electric buses from NYCT has shown that the emissions are considerably cleaner than those from a standard diesel bus, and the fuel economy is better. The emission testing results that follow come from two main sources: (1) a Northeast Advanced Vehicle Consortium (NAVC) report, "Hybrid-Electric Drive Heavy-Duty Vehicle Testing Project, Final Emissions Report" (M.J. Bradley 2000), and (2) emission testing by Environment Canada for acceptance testing of the NYCT Orion VI and Orion VII hybrid buses. In both cases, the emission testing was performed on a chassis dynamometer.

Testing for NAVC

The emission testing program for NAVC was performed by M.J. Bradley and Associates using the WVU chassis dynamometer laboratory. The testing was performed September through November 1999 in New York City. Several vehicles were tested; however, the focus here is on the results from four Orion VI diesel hybrids from the older hybrid fleet and three NovaBUS RTS diesel buses from the same bus order as the diesel buses tested in this evaluation from the Manhattanville Depot. The buses for the evaluation were chosen at random from the fleet of that type.

The dynamometer testing for the NAVC report was completed on three different bus duty cycles. The CBD cycle has an average speed of 12.6 mph, which is nearly double the average speed calculated for the Manhattanville Depot (6.43 mph). The CBD cycle is typically used for emission and fuel economy testing for transit buses.

The New York bus cycle was developed from real in-service time versus distance data collection and has an average speed of 3.7 mph, which is 42% lower than the average speed calculated for the Manhattanville Depot.

The third cycle was developed by collecting speed versus time data from one NYCT bus, before the NAVC testing. This cycle, the Manhattan cycle, has an average speed of 6.9 mph. Of the three cycles, the Manhattan cycle is the closest to actual operation evaluated in revenue service.

Figures 17 through 19 show results from the NAVC emissions tests using the WVU chassis dynamometer across all three test cycles. The fuel used was typical diesel fuel at NYCT, which is a Jet A formulation fuel similar to diesel #1 with standard specification for sulfur content. The hybrid buses were equipped with a catalyzed DPF from NETT Technologies, and the diesel buses had a standard catalytic converter.

The CBD cycle results (Figure 17) show that the CO was 97% lower, NO_x was 36% lower, HC were 43% lower, PM was 50% lower, and CO_2 was 19% lower for the hybrids compared to the diesel buses. For the CBD cycle, the fuel economy (miles per gallon) was 23% higher for the hybrid buses.

Results from the NY Bus cycle (Figure 18), with a much slower average speed, show that CO was 56% lower, NO_x was 44% lower, HC were 88% higher, PM was

Figure 17. Emission testing results for NAVC, CBD cycle

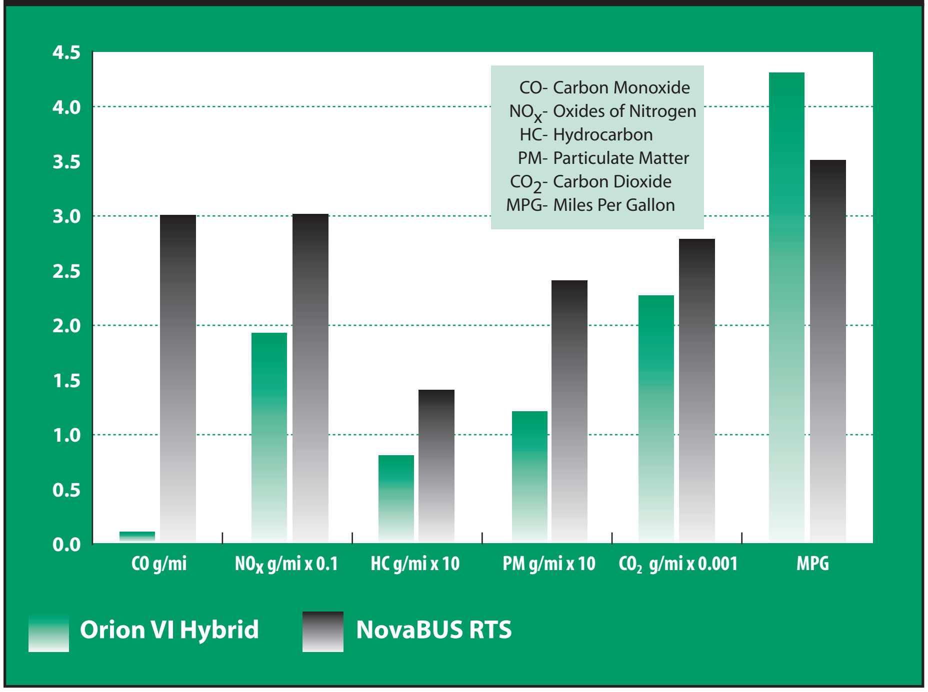
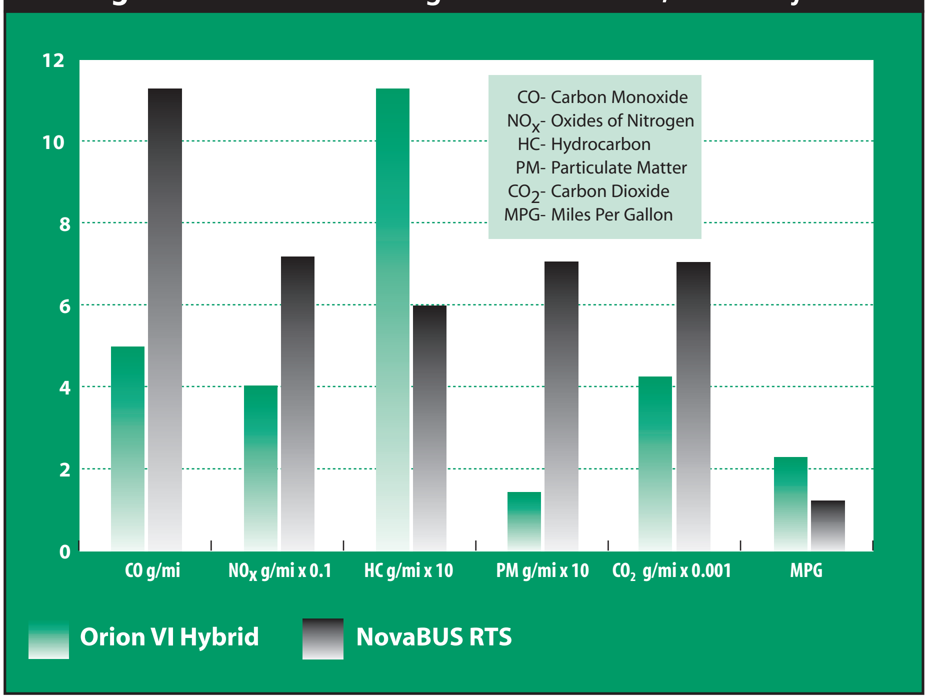


Figure 18. Emission testing results for NAVC, NY Bus cycle



77% lower, and CO_2 was 40% lower. The fuel economy was 64% higher for the hybrid buses on this slower operating cycle. The HC results were the only unexpected result, but the HC levels were relatively low to begin with in both fleets.

The Manhattan cycle (Figure 19), which was about the same average speed as the in-service buses, showed that CO was 98% lower, NO_x was 44% lower, HC were 28% lower, PM was at least 99% lower, and CO_2 was 33% lower. The fuel economy was 48% higher for the hybrid buses.

In general, these emission test results show that the hybrid buses were much cleaner than the diesel buses tested, except for the HC on the NY bus cycle. Some of the best emissions results were for the Manhattan cycle, which is the closest to how the buses are operated in service.

Testing by Environment Canada

Figure 20 shows results for separate tests of Orion V diesel buses with and without catalyzed DPFs installed, compared with results for the next-generation Orion VII diesel hybrid-electric bus representative of the upcoming NYCT order.

Testing was performed by Environment Canada on one diesel hybrid-electric bus and two diesel buses in February 2000 using the Environment Canada dynamometer located in Ottawa, Canada.

The Orion VII hybrid is configured with significant differences from the Orion VI hybrid, including a different engine (the Cummins ISB diesel engine) and an Engelhard DPX catalyzed DPF. The buses were tested on the CBD cycle and used ULSD #1 fuel with sulfur content less than 30 ppm.

The results in Figure 20 include the Orion V diesel buses being tested first without the catalyzed DPF and then with a Johnson Matthey CRT catalyzed DPF. The results of the Orion VII hybrid compared with the Orion V diesel without a catalyzed DPF are as follows: CO was 94% lower, NO_x was 49% lower, HC were 120% higher, PM was 93% lower, and CO_2 was 37% lower for the hybrid buses. The fuel economy was 54% higher for the hybrid buses. The HC results were higher for the hybrid buses, but both buses had low HC results.

The results in Figure 20 for the Orion VII hybrid compared with the Orion V diesel buses with a catalyzed DPF are as follows: CO was 38% lower, NO_x was 49% lower, HC were 450% higher, PM was 60% lower, and CO_2 was 38% lower for the hybrid buses. The fuel economy was 59% higher for the hybrid buses. With and without the catalyzed DPF, the HC emissions were lower for the diesel bus results; however, the HC results were very low for all results shown.

Figure 19. Emission testing results for NAVC, Manhattan cycle

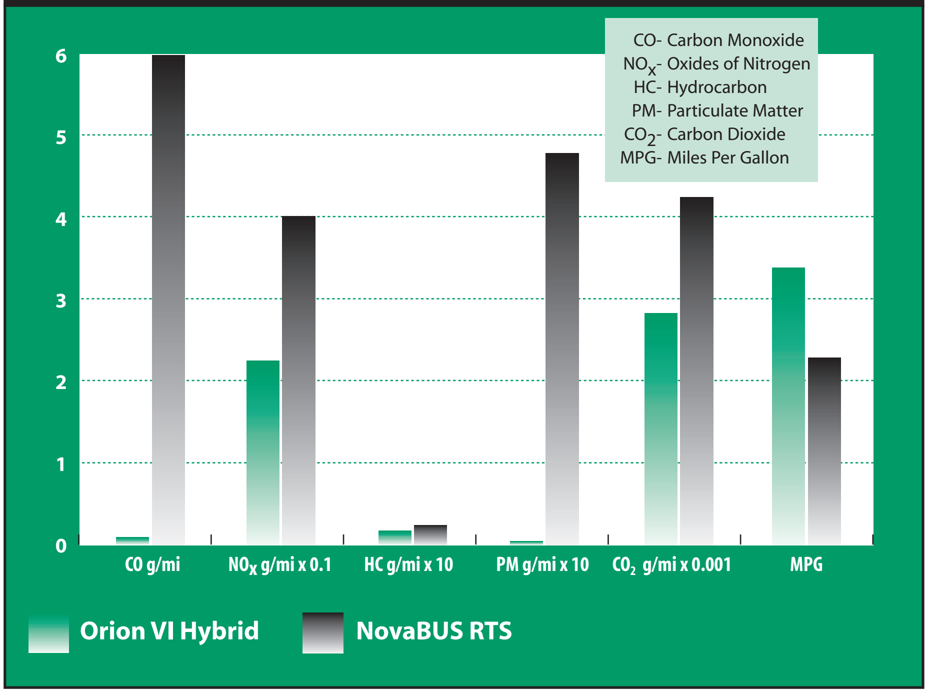
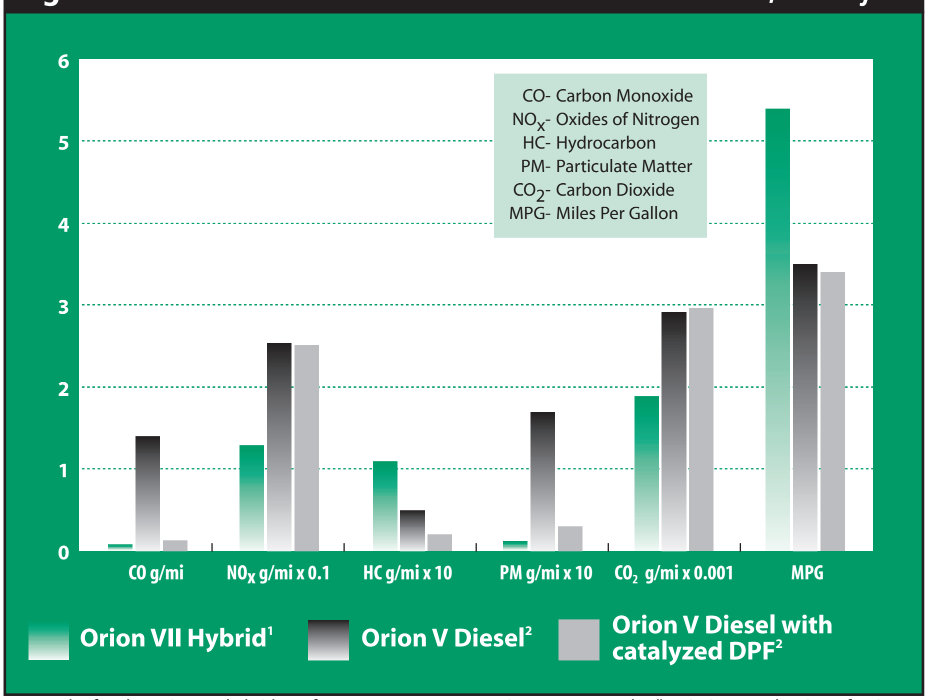


Figure 20. Emission test results from Environment Canada, CBD cycle



1. Results for the Orion VII hybrid are from Report #01-12, Environment Canada, "Emissions Evaluation of Orion VII Hybrid Bus with BAE SYSTEMS Controls HybriDrive™ Propulsion System."
2. Results for Orion V diesel buses from the same order as the buses tracked in this report from Amsterdam Depot, SAE Paper 2001-01-0511, "Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit." These tests were also performed at Environment Canada.

Summary and Conclusions

Based on the evaluation of the NYCT diesel hybrid-electric transit buses, we can conclude that the pilot demonstration achieved almost all of its original goals:

- Emission reduction goals, for both NO_x (<15 g/mi) and PM (<0.06 g/mi), were easily met.
- In-service average fuel economy for the hybrid fleet was 10% greater than that of the comparable diesel bus fleet; however, the in-service data showed that, in some months, the hybrid bus fuel economy reached as high as 22% better than the diesel buses operating in similar service. Fuel economy, as measured during emission testing, showed a potential improvement for the hybrid buses of 23%–64% compared to diesel buses of a similar age. In-service fuel economy improved and is expected to continue to improve with the Orion VII.
- The hybrid buses have been operated in a seamless fashion from the Manhattanville Depot; drivers and dispatchers report no restrictions for the hybrid buses.
- Drivers reported that the hybrid bus performance (e.g., acceleration, gradability, and range) was as good or better than the diesel buses and there are no significant differences in operation.
- Drivers reported that they liked the hybrid buses, and that passengers usually do not notice that the buses are hybrid-electric. When passengers do notice, they appear to be impressed with the new technology.
- The goal to increase brake life significantly has not been proven in this evaluation because the duration of this data collection and evaluation was not sufficient to compare bus brake lifetimes. The maintenance staff at Manhattanville Depot indicates that the brake life on the hybrid buses may be two to three times longer than on the diesel buses.
- NYCT is heavily invested in hybrid bus technology with orders of 325 more hybrid buses and a planned order of another 50 hybrid buses.

In addition, the following conclusions were reached:

- During the evaluation, the hybrid buses had overall operating costs (excluding driver labor) 46%–92% higher than the NovaBUS RTS diesel buses. Much of this difference was caused by higher labor hours required to repair and maintain all bus subsystems on the 10 prototype hybrid buses, including the hybrid propulsion system.
- The hybrid buses were driven 30%–45% fewer miles during the evaluation period, compared with the diesel buses, because of the need to service the prototype hybrid buses and the extra time required to

coordinate with the manufacturers to troubleshoot and fix those problems.

- Maintenance costs were 76%–150% higher for the hybrid buses than for the diesel buses, owing mostly to early problems with the engine and fuel-related systems (primarily the hybrid propulsion system), the unfamiliarity of the system to the service technicians at NYCT, difficulty in troubleshooting problems and in obtaining repair parts for the hybrid vehicles due to their pre-production status, and the fact that the hybrid fleet represented only a small percentage of the total buses at the operating location. Maintenance costs for hybrid buses are expected to fall significantly for the second generation of vehicles, which will be produced and delivered in much higher quantities.
- The facility conversion for accommodating hybrid buses was minor compared to preparing for CNG facilities.

Future Hybrid Vehicle and Alternative Fuel Operations at NYCT

NYCT continues its commitment to a cleaner emission fleet of buses. The NYCT bus fleet currently consists of 4,489 buses with 10 hybrid buses, 221 CNG buses, and 4,258 standard diesel buses. NYCT plans to operate 385 diesel hybrid buses, 646 CNG buses, and the remaining diesel buses retrofitted with catalyzed DPFs by 2006. NYCT also plans to purchase additional new diesel buses with catalyzed DPFs installed.

To support the use of catalyzed DPFs, NYCT specified ULSD fuel with sulfur content less than 30 ppm. This fuel allows the use of more active catalysts in the catalyzed DPFs and a greater reduction of PM and HC in the exhaust of the bus engine.

As of the end of the data collection period (mid-2001), NYCT has 10 Orion VI diesel hybrids with a BAE SYSTEMS HybriDrive™ propulsion system and a DDC/International Series 30D/T444E engine used as the power plant. The next order of hybrid buses is for 125 Orion VII diesel hybrid buses, to be delivered starting in 2002, with a BAE SYSTEMS HybriDrive™ propulsion system and a Cummins ISB engine used for the power plant. Other orders for 250 diesel hybrid-electric buses are in progress, for delivery between now and 2006.

The Manhattanville Depot is to be converted to accommodate CNG buses. The 10 Orion VI hybrid buses and the 125 new hybrid buses will be split between two other depots, Mother Clara Hale and Queens Village. The hybrid bus fleet will soon make up about 30% of the fleet at each depot and will require the depot's close attention to keep the buses in service as staff learn about the new technology.

A new capital spending plan for NYCT, for bus purchases from 2005 through 2009, may include more CNG, hybrid, and possibly fuel cell bus purchases (at least for demonstration purposes).

What's Next for NYCT?

The next fleet of hybrid buses at NYCT (the order of 125 hybrid buses) is expected to be a nearly full-service, commercial product. The Orion VII hybrid bus uses the BAE SYSTEMS HybriDrive™ propulsion system and has been designed to incorporate all of the technical lessons learned from the experience with the Orion VI hybrid buses. Some of the design changes include the following:

- The Cummins ISB engine with an Engelhard DPX catalyzed DPF is being used for the power plant.
- The traction motor and generator design have been improved for reliability and performance.
- The connection of the engine and the generator has been changed to allow the hybrid diesel engine to be mounted in a similar fashion as a standard diesel bus engine. This should provide easier access to the engine.
- The rear axle is standard, since the bus design has a step up in the back, rather than fully low floor. This should reduce brake repair costs.
- Many software changes have been made to optimize the operation of the hybrid propulsion system.

The Orion VII diesel hybrid-electric bus design is expected to be more fully optimized for fuel economy, specifically regenerative braking and hybrid controls. Future design changes may include ultracapacitors in conjunction or in place of the batteries to more efficiently and quickly control the flow of power to and from the drive train.

The goals for the operation of the newer hybrid buses are similar to the original 10 buses but are now more focused on reliability and optimization for cost of operation:

- Significantly reduce bus fleet emissions.
- Significantly increase fuel economy.
- Show that the hybrid buses are commercially viable, i.e., hybrids can be purchased in volume with standard terms and conditions to replace conventional diesel buses.
- Demonstrate rapid deployment of a large number of hybrid buses with minimal infrastructure investment or service capacity interruption (especially compared to CNG bus operation).
- Demonstrate that hybrid buses can be reliable and cost-effective in providing regular revenue service.

NREL plans to implement a follow-up evaluation of the Orion VII hybrid bus order at NYCT starting as soon as early 2003.

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Appendix A

Fleet Summary Statistics

New York City Transit (New York, NY) Fleet Summary Statistics

Evaluation Period 4/1/02

Fleet Operations and Economics

	Diesel AMS	Diesel MV	Older Hybrid 6351-4	Newer Hybrid 6355-9
Number of Vehicles	7	7	4	5
Period Used for Fuel and Oil Op Analysis	7/00 - 9/01	7/00 - 9/01	7/00 - 9/01	7/00 - 9/01
Total Number of Months in Period	15	15	15	15
Fuel and Oil Analysis Base Fleet Mileage	230,021	229,993	60,146	114,319
Period Used for Maintenance Op Analysis	4/99 - 6/00	4/99 - 4/00	9/98 - 5/01	9/98 - 5/01
Total Number of Months in Period	12	12	12	12
Maintenance Analysis Base Fleet Mileage	203,638	219,728	60,942	106,629
Average Monthly Mileage per Vehicle	2,333	2,341	1,283	1,632
Fleet Fuel Usage in Gal.	105,804	95,025	22,773	42,962
Representative Fleet MPG	2.17	2.42	2.64	2.66
Ratio of MPG (AT/DC)			1.09	1.10
Average Fuel Cost as Reported (with tax)	1.03	1.03	1.03	1.03
	per Gal JetA	per Gal JetA	per Gal JetA	per Gal JetA
Average Fuel Cost per Energy Equivalent	1.03	1.03	1.03	1.03
Fuel Cost per Mile	0.474	0.426	0.390	0.387
Number of Total Roadcalls	94	129	88	124
MBRC All Roadcalls	2,166	1,703	693	860
Number of Engine/Fuel Roadcalls	13	21	38	43
MBRC Engine/Fuel Roadcalls	15,664	10,463	1,604	2,480
Total Scheduled Repair Cost per Mile	0.195	0.242	0.230	0.291
Total Unscheduled Repair Cost per Mile	0.420	0.530	1.666	1.071
Total Maintenance Cost per Mile	0.615	0.772	1.896	1.362
Total Operating Cost per Mile	**1.089**	**1.198**	**2.286**	**1.749**

Maintenance Costs

	Diesel AMS	Diesel MV	Older Hybrid 6351-4	Newer Hybrid 6355-9
Fleet Mileage	203,638	219,728	60,942	106,629
Total Parts Cost	21,338.90	19,868.08	12,495.68	17,306.00
Total Labor Hours	2078.8	2996.6	2061.2	2557.9
Average Labor Cost	103,940.55	149,831.60	103,059.70	127,895.90
(@ $50.00 per hour)				
Total Maintenance Cost	125,279.45	169,699.68	115,555.38	145,201.90
Total Maintenance Cost per Mile	**0.615**	**0.772**	**1.896**	**1.362**

Breakdown of Maintenance Costs by Vehicle System

	Diesel AMS	Diesel MV	Older Hybrid 6351-4	Newer Hybrid 6355-9
Fleet Mileage	203,638	219,728	60,942	106,629
Total Engine/Fuel-Related and Transmission Systems (ATA VMRS 27, 30, 31, 32, 33, 41, 42, 43, 44, 45, 46)				
Parts Cost	3,604.99	4,119.34	2,222.10	3,947.67
Labor Hours	236.1	264.3	608.5	692.3
Average Labor Cost	11,804.80	13,214.35	30,423.60	34,614.10
Total Cost (for system)	15,409.79	17,333.69	32,645.70	38,561.77
Total Cost (for system) per Mile	**0.0757**	**0.0789**	**0.5357**	**0.3616**
Exhaust System Repairs (ATA VMRS 43)				
Parts Cost	10.00	58.18	40.00	55.00
Labor Hours	9.5	43.9	15.5	60.5
Average Labor Cost	473.65	2,195.00	775.00	3,025.00
Total Cost (for system)	483.65	2,253.18	815.00	3,080.00
Total Cost (for system) per Mile	**0.0024**	**0.0103**	**0.0134**	**0.0289**
Fuel System Repairs (ATA VMRS 44)				
Parts Cost	151.39	136.31	143.44	376.91
Labor Hours	22.1	11.2	74.0	65.8
Average Labor Cost	1,105.70	558.35	3,700.00	3,287.50
Total Cost (for system)	1,257.09	694.66	3,843.44	3,664.41
Total Cost (for system) per Mile	**0.0062**	**0.0032**	**0.0631**	**0.0344**
Power Plant (Engine) Repairs (ATA VMRS 45)				
Parts Cost	2,212.46	2,564.23	995.57	1,627.97
Labor Hours	31.7	72.6	146.0	212.6
Average Labor Cost	1,583.35	3,629.20	7,300.70	10,630.75
Total Cost (for system)	3,795.81	6,193.43	8,296.27	12,258.72
Total Cost (for system) per Mile	**0.0186**	**0.0282**	**0.1361**	**0.1150**
Electric Motor, Generator, and Battery Repairs (ATA VMRS 46)				
Parts Cost	0.00	0.00	236.35	692.51
Labor Hours	0.0	0.0	260.5	144.5
Average Labor Cost	0.00	0.00	13,025.00	7,225.00
Total Cost (for system)	0.00	0.00	13,261.35	7,917.51
Total Cost (for system) per Mile	**0.0000**	**0.0000**	**0.2176**	**0.0743**
Electrical System Repairs (ATA VMRS 30-Electrical General, 31-Charging, 32-Cranking, 33-Ignition)				
Parts Cost	434.80	685.70	416.01	507.72
Labor Hours	61.2	53.7	44.7	68.3
Average Labor Cost	3,060.65	2,686.95	2,234.50	3,412.50
Total Cost (for system)	3,495.45	3,372.65	2,650.51	3,920.22
Total Cost (for system) per Mile	**0.0172**	**0.0153**	**0.0435**	**0.0368**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel AMS	Diesel MV	Older Hybrid 6351-4	Newer Hybrid 6355-9
Air Intake System Repairs (ATA VMRS 41)				
Parts Cost	239.55	311.05	160.70	460.78
Labor Hours	3.2	14.0	0.0	10.5
Average Labor Cost	161.65	699.00	0.90	525.00
Total Cost (for system)	401.20	1,010.05	161.60	985.78
Total Cost (for system) per Mile	**0.0020**	**0.0046**	**0.0027**	**0.0092**
Cooling System Repairs (ATA VMRS 42)				
Parts Cost	108.12	148.91	230.03	198.23
Labor Hours	49.1	41.4	39.8	118.7
Average Labor Cost	2,454.15	2,070.85	1,987.50	5,933.35
Total Cost (for system)	2,562.27	2,219.76	2,217.53	6,131.58
Total Cost (for system) per Mile	**0.0126**	**0.0101**	**0.0364**	**0.0575**
Brake System Repairs (ATA VMRS 13)				
Parts Cost	3,338.64	4,532.41	570.41	1,157.17
Labor Hours	228.2	738.6	192.5	269.2
Average Labor Cost	11,409.45	36,929.30	9,625.10	13,458.35
Total Cost (for system)	14,748.09	41,461.71	10,195.51	14,615.52
Total Cost (for system) per Mile	**0.0724**	**0.1887**	**0.1673**	**0.1371**
Transmission Repairs (ATA VMRS 27)				
Parts Cost	448.67	214.97	0.00	28.55
Labor Hours	59.3	27.5	28.0	11.5
Average Labor Cost	1,482.83	1,375.00	1,400.00	575.00
Total Cost (for system)	1,931.50	1,589.97	1,400.00	603.55
Total Cost (for system) per Mile	**0.0095**	**0.0072**	**0.0230**	**0.0057**
Cab, Body, and Accessories Systems Repairs (ATA VMRS 02-Cab and Sheet Metal, 50-Accessories, 71-Body)				
Parts Cost	9,408.29	5,773.33	5,371.74	7,928.92
Labor Hours	750.5	810.0	567.1	584.7
Average Labor Cost	37,523.15	40,501.95	28,356.85	29,234.85
Total Cost (for system)	46,931.44	46,275.28	33,728.59	37,163.77
Total Cost (for system) per Mile	**0.2305**	**0.2106**	**0.5535**	**0.3485**
Inspections Only - no parts replacements (101)				
Parts Cost	0.00	0.00	0.00	0.00
Labor Hours	305.7	520.4	166.0	397.6
Average Labor Cost	15,285.50	26,019.65	8,298.50	19,880.45
Total Cost (for system)	15,285.50	26,019.65	8,298.50	19,880.45
Total Cost (for system) per Mile	**0.0751**	**0.1184**	**0.1362**	**0.1864**

Breakdown of Maintenance Costs by Vehicle System (continued)

	Diesel AMS	Diesel MV	Older Hybrid 6351-4	Newer Hybrid 6355-9
HVAC System Repairs (ATA VMRS 01)				
Parts Cost	2,934.66	2,869.30	3,020.98	2,693.81
Labor Hours	269.6	332.2	128.8	219.5
Average Labor Cost	13,478.90	16,608.10	6,437.50	10,973.65
Total Cost (for system)	16,413.56	19,477.40	9,458.48	13,667.46
Total Cost (for system) per Mile	**0.0806**	**0.0886**	**0.1552**	**0.1282**
Air System Repairs (ATA VMRS 10)				
Parts Cost	45.64	140.60	102.59	178.51
Labor Hours	4.8	40.9	83.3	69.3
Average Labor Cost	237.50	2,047.00	4,162.50	3,462.50
Total Cost (for system)	283.14	2,187.60	4,265.09	3,641.01
Total Cost (for system) per Mile	**0.0014**	**0.0100**	**0.0700**	**0.0341**
Lighting System Repairs (ATA VMRS 34)				
Parts Cost	326.09	253.46	313.67	430.90
Labor Hours	132.1	78.8	72.5	80.0
Average Labor Cost	6,605.45	3,937.50	3,625.00	4,000.00
Total Cost (for system)	6,931.54	4,190.96	3,938.67	4,430.90
Total Cost (for system) per Mile	**0.0340**	**0.0191**	**0.0646**	**0.0416**
Frame, Steering, and Suspension Repairs (ATA VMRS 14-Frame, 15-Steering, 16-Suspension)				
Parts Cost	757.76	1,823.07	808.46	826.15
Labor Hours	93.8	159.9	172.1	191.8
Average Labor Cost	4,689.55	7,992.65	8,606.85	9,587.50
Total Cost (for system)	5,447.31	9,815.72	9,415.31	10,413.65
Total Cost (for system) per Mile	**0.0267**	**0.0447**	**0.1545**	**0.0977**
Axle, Wheel, and Drive Shaft Repairs (ATA VMRS 11-Front Axle, 18-Wheels, 22-Rear Axle, 24-Drive Shaft)				
Parts Cost	128.11	49.42	0.00	42.36
Labor Hours	19.3	22.5	31.8	22.1
Average Labor Cost	964.55	1,123.00	1,589.30	1,105.30
Total Cost (for system)	1,092.66	1,172.42	1,589.30	1,147.66
Total Cost (for system) per Mile	**0.0054**	**0.0053**	**0.0261**	**0.0108**
Tire Repairs (ATA VMRS 17)				
Parts Cost	0.00	0.00	0.00	9.68
Labor Hours	5.3	29.2	18.7	19.5
Average Labor Cost	266.70	1,458.10	934.50	977.45
Total Cost (for system)	266.70	1,458.10	934.50	987.13
Total Cost (for system) per Mile	**0.0013**	**0.0066**	**0.0153**	**0.0093**
Hydraulic Repairs (ATA VMRS 65)				
Parts Cost	794.73	264.06	85.73	90.83
Labor Hours	33.5	0.0	20.0	9.0
Average Labor Cost	1,675.00	0.00	1,000.00	450.00
Total Cost (for system)	2,469.73	264.06	1,085.73	540.83
Total Cost (for system) per Mile	**0.0121**	**0.0012**	**0.0178**	**0.0051**

Notes

1. The engine- and fuel-related systems were chosen to include only those systems of the vehicles that could be directly a part of the propulsion system.

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

3. In general, inspections (with no part replacements) were 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.

Appendix B

Emission Test
Results

Table B-1. Emissions Test Results from Hybrid and Diesel Buses Tested by WVU

Cycle	Bus	CO	NO_x	HC	PM	CO_2	MPG
		g/mi	g/mi	g/mi	g/mi	g/mi	
CBD	Orion Hybrid	0.1	19.2	0.08	0.12	2262	4.3
CBD	NovaBUS RTS	3.0	30.1	0.14	0.24	2779	3.5
CBD	**Hybrid/Diesel**	**-97%**	**-36%**	**-43%**	**-50%**	**-19%**	**+23%**
NY Bus	Orion Hybrid	5.0	40.5	1.13	0.16	4251	2.3
NY Bus	NovaBUS RTS	11.3	72.0	0.60	0.70	7076	1.4
NY Bus	**Hybrid/Diesel**	**-56%**	**-44%**	**+88%**	**-77%**	**-40%**	**+64%**
Manhattan	Orion Hybrid	0.1	22.6	0.18	<0.005	2841	3.4
Manhattan	NovaBUS RTS	6.0	40.3	0.25	0.48	4268	2.3
Manhattan	**Hybrid/Diesel**	**-98%**	**-44%**	**-28%**	**-99%**	**-33%**	**+48%**

Table B-2. Emissions Test Results from Environment Canada Chassis Dynamometer

Cycle	Bus	CO	NO_x	HC	PM	CO_2	MPG
		g/mi	g/mi	g/mi	g/mi	g/mi	
CBD	Orion VII Hybrid[1]	0.08	12.9	0.11	0.012	1848	5.4
CBD	Orion V Diesel[2]	1.4	25.4	0.05	0.17	2916	3.5
CBD	Orion V Diesel with catalyzed DPF[2]	0.13	25.1	0.02	0.03	2958	3.4
CBD	**Hybrid/Diesel**	**-94%**	**-49%**	**+120%**	**-93%**	**-37%**	**+54%**
CBD	**Hybrid/Diesel with catalyzed DPF**	**-38%**	**-49%**	**+450%**	**-60%**	**-38%**	**+59%**

1. Results for the Orion VII Hybrid are from Report #01-12, Environment Canada, "Emissions Evaluation of Orion VII Hybrid Bus with BAE SYSTEMS Controls HybriDriveTM Propulsion System."

2. Results for Orion V diesel buses from the same order as the buses tracked in this report from Amsterdam Depot, SAE Paper 2001-01-0511, "Performance and Durability Evaluation of Continuously Regenerating Particulate Filters on Diesel Powered Urban Buses at NY City Transit." These tests were also performed at Environment Canada.

All results in Tables B-1 and B-2 for the hybrid buses have been corrected for state of charge (SOC) of the traction batteries on board. The SOC of the batteries can have a significant impact on the fuel economy calculations because of the need to understand the amount of energy consumed during the testing.

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

NREL
1617 Cole Blvd.
Golden, CO 80401-3393

NREL/BR-540-32427
July 2002

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