STUDY UPDATE:
BUS PROPULSION TECHNOLOGIES APPLICABLE IN CONNECTICUT

MARCH, 2003

A REPORT BY

THE CONNECTICUT ACADEMY OF SCIENCE AND ENGINEERING

FOR

THE CONNECTICUT DEPARTMENT OF TRANSPORTATION

AND

CTTRANSIT™

Connecticut Academy of Science and Engineering

The Connecticut Academy is a non-profit institution patterned after the National Academy of Sciences to identify and study issues and technological advancements that are or should be of concern to the state of Connecticut. It was founded in 1976 by Special Act of the Connecticut General Assembly.

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The Connecticut Academy will foster an environment in Connecticut where scientific and technological creativity can thrive and contribute to Connecticut becoming a leading place in the country to live, work and produce for all its citizens, who will continue to enjoy economic well- being and a high quality of life.

Mission Statement

The Connecticut Academy will provide expert guidance on science and technology to the people and to the State of Connecticut, and promote its application to human welfare and economic well being.

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- Provide information and advice on science and technology to the government, industry and people of Connecticut.

- Initiate activities that foster science and engineering education of the highest quality, and promote interest in science and engineering on the part of the public, especially young people.

- Provide opportunities for both specialized and interdisciplinary discourse among its own members, members of the broader technical community, and the community at large.

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ORIGIN OF INQUIRY:	CONNECTICUT DEPARTMENT OF TRANSPORTATION
DATE INQUIRY ESTABLISHED:	DECEMBER 18, 2002
DATE RESPONSE: RELEASED:	MARCH 21, 2003

This limited-scope study was conducted by Academy Member Dr. George Foyt. The content of this report lies within the province of the Academy's Technical Board on Transportation Systems, and has been reviewed by Mr. Herbert S. Levinson, Chairman, Transportation Systems Technical Board and Mr. Gale Hoffnagle, Academy Council Member. Ms. Martha Sherman, the Academy's Managing Editor, edited the report. The report is hereby released with the approval of the Academy Council.

Richard H. Strauss
Executive Director

EXECUTIVE SUMMARY

STUDY OBJECTIVES

The Connecticut Academy of Science and Engineering (the "Academy") was asked by the Connecticut Department of Transportation (CONN-DOT) to update the *Study of Bus Propulsion Technologies Applicable in Connecticut* ("*BPT2001")* of February 2001, prepared for CONN-DOT and CTTRANSIT™, focusing on propulsion technology developments that will be available for fleet purchase in the "near term" (~1 to 4 years).

This update includes changes and updates on:

- Conventional diesel technology
- Hybrid diesel-electric propulsion technology
- LNG and CNG fuel options
- All-electric propulsion, including the requirements of:
    - Minimum range capability of 120 miles
    - Fast recharge capability
- A review of the zinc/air battery propulsion technology

The conventional diesel, hybrid diesel-electric, liquefied natural gas (LNG) and compressed natural gas (CNG) sections of this report, as in the original report, discuss:

- Bus Availability
- Bus Emissions: A review of several comparison studies
- Bus Reliability: A review of two studies
- Bus Costs

Overview

The current markets and findings are similar to those found in the Academy's earlier *BPT2001* report. However, there are specific issues and developments that have occurred since the issuance of the *BPT2001* report that are of interest, as follows:

- Recent operational experience of conventional diesel buses, equipped with state-of-the-art exhaust gas treatment systems and running on ultra-low-sulfur-fuel, has validated the *BPT2001* report's expectation that these buses are capable of very reliable operation and very low levels of emissions.

- A second-generation hybrid diesel-electric bus is currently available on the market. The design of this bus (a parallel-style hybrid, in which the drive wheels are powered by both a diesel engine and an electric motor) offers some operational advantages over the first generation hybrid bus (a series-style hybrid, in which only the electric motor powers the drive wheels), however, its reliability needs to be established.

Bus Availability

Heavy-duty 40-foot transit buses continue to be available and are sold with conventional diesel, hybrid diesel-electric, CNG, and LNG fueled propulsion systems.

Bus Emissions

Conventional diesel buses equipped with state-of-the-art exhaust gas treatment systems and running on ultra-low-sulfur fuel, similar hybrid diesel-electric buses, CNG buses, and LNG buses are all capable of operation at very low emission levels for Particulate Matter (PM) and Carbon Monoxide (CO). However CNG and LNG buses have considerably higher emission levels of Total Hydrocarbons (THC) and Non-Methane Hydrocarbons (NMHC).

Bus Reliability

Conventional diesel buses remain the standard for reliable bus operation. In comparison tests reported by the New York City Transit Authority, the "Orion" hybrid diesel-electric buses, recently demonstrated Mean Time Between Failure (MTBF) values slightly greater than one-half those of conventional diesel buses (~1300 hours vs. ~2300 hours). In similar tests reported by the San Francisco Municipal Railway, the values for MTBF were ~400 to 450 hours for both CNG and hybrid buses vs. ~650 hours for diesel buses.

Bus Cost

Both CNG and hybrid diesel-electric buses have higher purchase prices than equivalent conventional diesel buses (~$390K for CNG and hybrids vs. ~$340K for diesel). Note that, as indicated by these prices, the additional cost premium compared to diesel for either CNG or hybrid buses purchased in quantity, is now about the same. This is in contrast to the earlier *BPT2001* report in which the cost of CNG buses (and therefore the premium also) was substantially less than hybrid buses. Additionally, as stated in the *BPT2001* report, the infrastructure costs for the operation of CNG buses are higher to substantially higher than for other types, varying on a case-by-case basis.

All-Electric Buses

There are currently only two types of all-electric or essentially all-electric, battery-powered, buses available on the market with specified ranges of 100 miles or greater. There is only one supplier for each type of bus:

- A 30-foot bus, a demonstration project in Santa Barbara, CA, has reportedly been well received by both drivers and riders.
- A 40-foot bus is brand new to the market, and has some operational issues that make it unattractive for fleet operation.

RECOMMENDATIONS

Consistent with the recommendations of the *BPT2001* report, Connecticut should continue to concentrate its bus acquisition program on the purchase of conventional diesel buses equipped with state-of-the-art exhaust gas treatment systems and running on ultra-low-sulfur fuel. All of the recent experience and research points to this technology as a widely available, low emission level, and very reliable solution with the lowest purchase and infrastructure costs.

Also, reinforcing the findings of the *BPT2001* report, it is recommended that Connecticut explore the hybrid diesel-electric technology by purchasing a small number of such buses and evaluating their operation on state bus routes. However, it is now recommended to proceed more slowly with this option than was indicated in the *BPT2001* report. The reliability of the first generation of these buses has been significantly poorer than equivalent conventional diesel buses, and the number of suppliers continues to be small. Nevertheless, the inherent technical and operational advantages of hybrid diesel-electric buses merit continued exploration of this option, with the expectation that future generations of these buses will overcome the reliability issues, and that there will be an adequate number of suppliers.

Finally, it is recommended that Connecticut continue to monitor the development progress of all-electric buses.

TABLE OF CONTENTS

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BUS TECHNOLOGY REVIEW

I. BUS AVAILABILITY

Standard size heavy-duty 40-foot buses continue to be available and are sold with propulsion systems that include:

- Conventional diesel
- Conventional diesel with state-of-the-art exhaust gas treatment systems
- Compressed natural gas (CNG)
- Liquefied natural gas (LNG)
- Hybrid diesel-electric

Although conventional diesel and variations continue to dominate the market, sales of CNG buses continue to be robust, LNG remains an option, and there are now two suppliers of hybrid diesel-electric buses. CNG and LNG sales are substantially concentrated in warmer climates (California and Texas), conventional diesel sales are countrywide, and hybrid diesel-electric sales are substantially concentrated in the northeast, with New York City Transit (NYCT) as the dominant purchaser.

II. BUS EMISSIONS

Recent bus emissions reports have been issued by the:

- New York City Transit Authority (*Reference 1*)
- California EPA, Air Resources Board (*Reference 2*)
- Allison Transmission Company (*Reference 3*)

Although the details varied among these reports, the following overall comments pertain to:

- Conventional diesel propulsion buses: The levels of particulate matter (PM), carbon monoxide (CO), and total hydrocarbons (THC) are greatly reduced by the use of state-of-the-art exhaust treatment systems, i.e. Johnson-Matthey Continuously Regenerating Technology systems, in combination with the use of ultra-low-sulfur (<15 ppm) fuel.

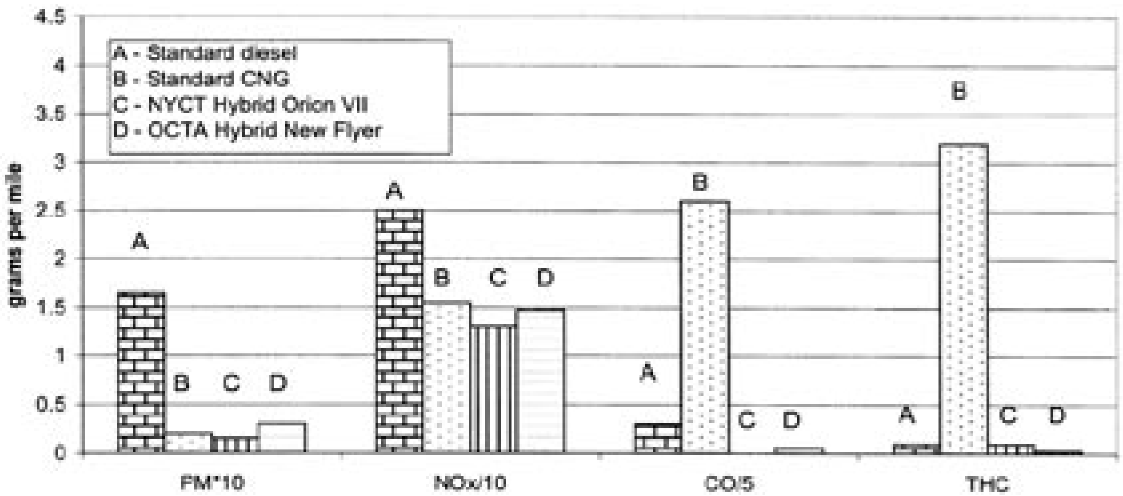
- All of the current propulsion technologies: The level of NOx emissions is relatively the same, depending on the details of the tests.

- CNG buses and the two hybrid diesel-electric buses evaluated in the NYCT report (*Ref. 1*): The particulate matter (PM) emission levels are greatly reduced, compared to standard diesel buses operated on conventional diesel fuel and without the latest exhaust gas treatment systems.

- CNG buses: These buses have much higher levels of carbon monoxide (CO) and total hydrocarbon (THC), emissions as compared to either conventional diesel buses or hybrid diesel-electric buses.

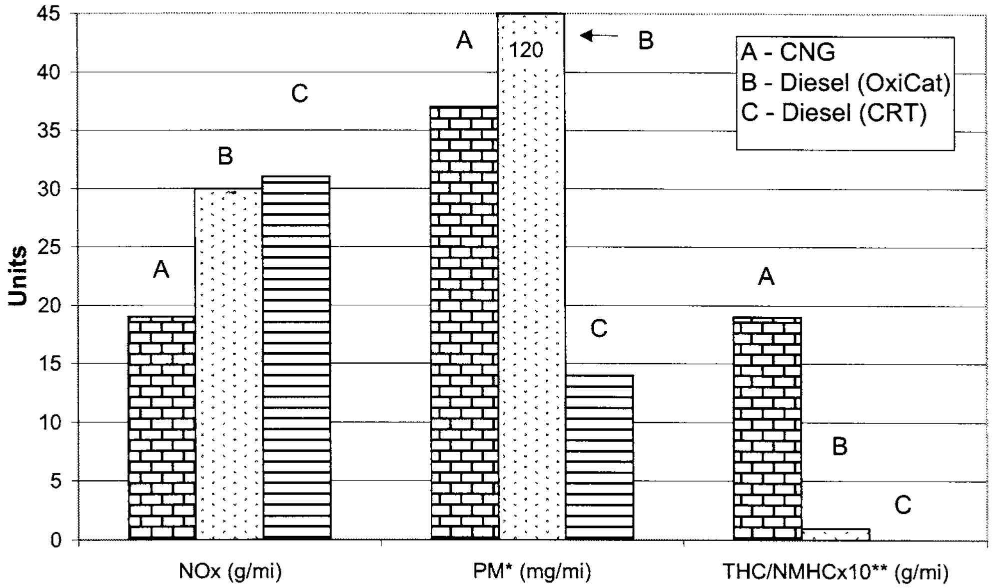
- The California Air Resources Board Study (*Ref. 2*): This study revealed that the total particulate matter emissions for a state-of-the-art CNG bus and a state-of-the-art diesel bus equipped with modern exhaust gas treatment were much lower than those for a conventional diesel bus. However, the study also revealed that the quantity of small particle emissions for the CNG bus was significantly greater than for the diesel bus, as much as ten times greater in the 8 nm size range. This is an especially interesting result, in view of the current discussion over the deleterious effects of very small dimension particulate matter on health.

FIGURE 1. EMISSION DATA FOR SEVERAL TYPES OF TRANSIT BUSES



Emission levels for several 40-foot transit buses operated on the Central Business District (CBD) cycle (NYCT Operating Experience with Hybrid Transit Buses, APTA/EPRI/EVAA, John Lowell, New York City Transit, Electric Bus Workshop, October 10, 2002), (Reference 1) `Please note that data from the Orange County Transit Authority (OCTA) have been included in the report.

FIGURE 2. EMISSION DATA FOR SEVERAL LATE-MODEL BUSES

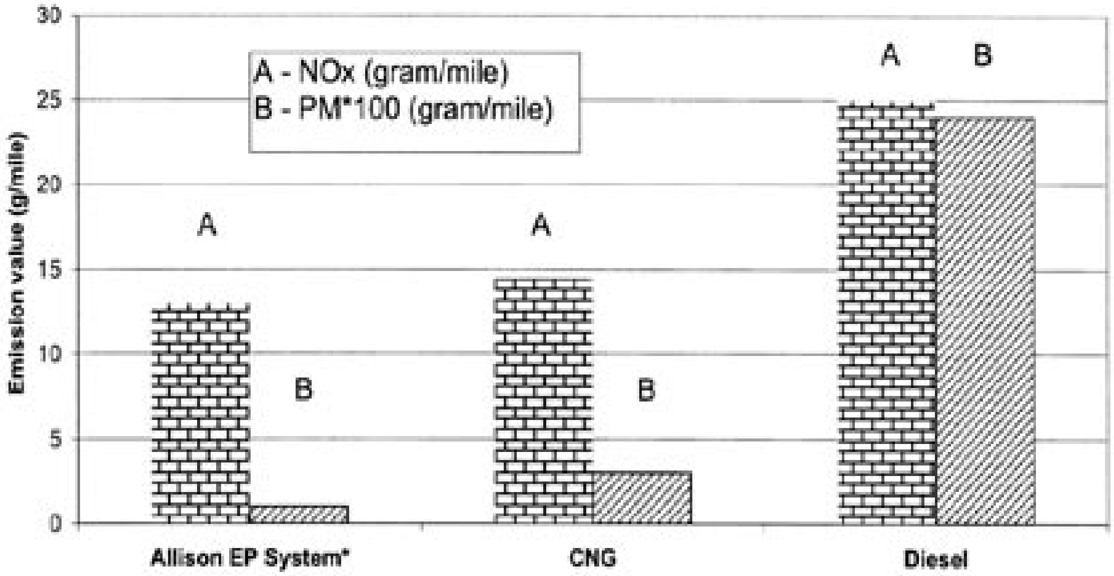


Emissions data from two late-model diesel and CNG heavy-duty transit buses (Alberto Ayala, et al, California Environmental Protection Agency, Air Resources Board, 12th CRC On-Road Vehicle Emissions Workshop, April 15-17, 2002, San Diego) (Reference 2)

Please note that:

1. *There are three scales of values represented here as shown in the abscissa labels.*
2. *The peak value for the OxiCat Diesel Particulate Matter is off-scale at 120 mg/ml.*
3. **The Particulate Matter (PM) is uncorrected for background.*
4. ***The total hydrocarbon/non-methane hydrocarbon (THC/NMHC) data value for the Continuously Regenerating Technology (CRT) bus is near the detection limit.*

FIGURE 3. EMISSION DATA FOR A CBD CYCLE

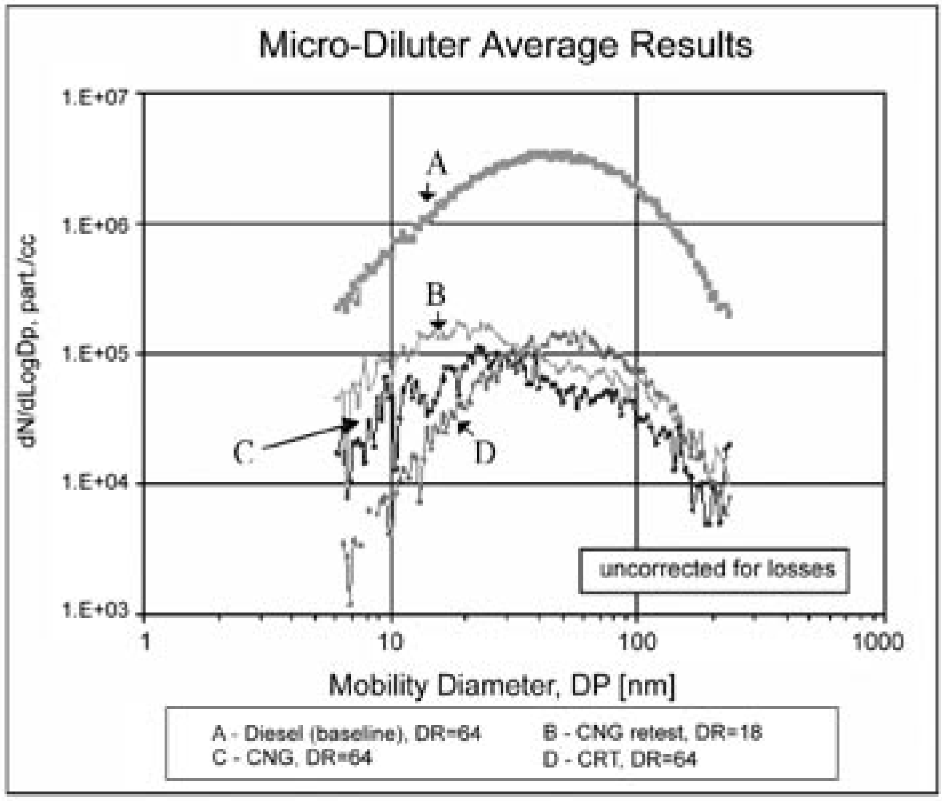


Urban Bus Emissions on a Central Business District (CBD) cycle. (From Allison, Inc. brochure, available at www.allisontransmission.com) (Reference 3)

Please note that:

1. **The Allison system data was taken with a discrete particulate filter (DPF) included in the system and using ultra low sulfur fuel at the Southwest Research Institute.*
2. *The CNG data was taken from the California Air Resources Board HD emissions lab report 01-01.*
3. *The diesel data was taken from the NAVC HD vehicle-testing project.*

FIGURE 4. PARTICLE SIZE DISTRIBUTIONS – STEADY STATE TESTS



Note: Diluted exhaust temperature ranged approximately from 80 to 90 F

Particle Size Distributions for several buses, including a conventional diesel bus (Baseline-top curve), a conventional CNG bus, a retest of the CNG bus, and a diesel bus fitted with a Johnson-Matthey Continuous Recycling Technology exhaust gas treatment filter (ARB's Study of Emissions from Two "Late-model" Diesel and CNG Heavy-duty Transit Buses, 12th CRC On-Road Vehicle Emissions Workshop, April 15-17, 2002, San Diego, CA) (Reference 2)

Source: 1) Holmén, B.A., and A. Ayala, "Ultrafine PM Emissions from Natural Gas, Oxidation-Catalyst Diesel and Particulate-Trap Diesel Heavy-Duty Transit Buses," Environ. Sci. Technol., 2002, submitted.

2) Holmén, B., A. Ayala, N. Kado, and R. Okamoto (2001). "ARB's Study of Emissions from "Late-model" Diesel and CNG Heavy-duty Transit Buses: Preliminary Nanoparticle Measurement Results," 5th International ETH Conference on Nanoparticle Measurements, Zürich.

III. BUS RELIABILITY

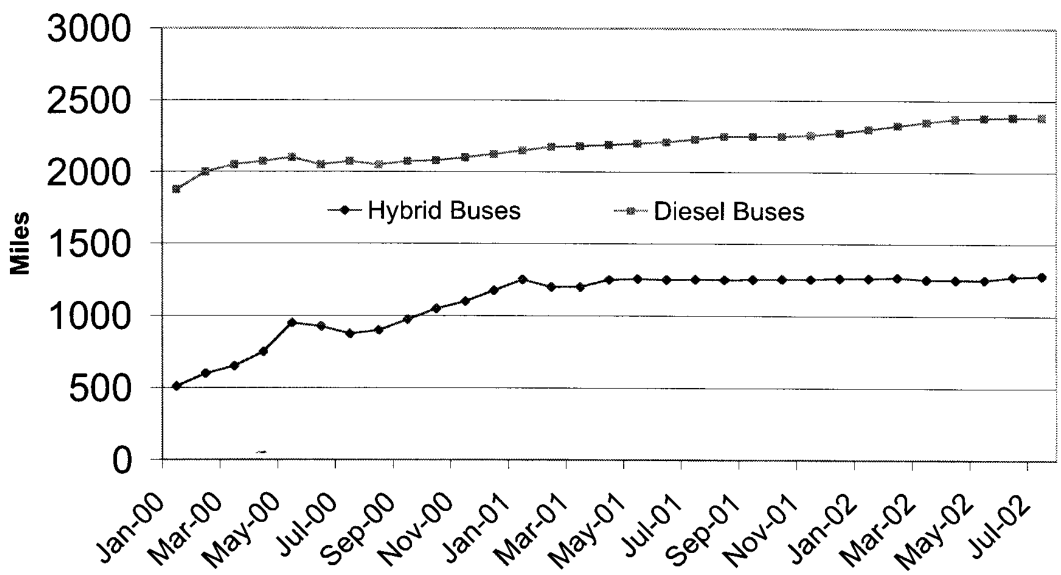
Recent reports that have been issued by NYCT, and by the San Francisco Municipal Railway reveal the following findings:

- Conventional diesel-powered buses are still the benchmark by which other propulsion technologies are measured.

- CNG powered buses, although relatively mature, have substantially lower mean time between failures (MTBF) than conventional diesels buses.

- Hybrid diesel-electric buses, although promising from a fundamental point of view, have substantially lower MTBFs than conventional diesel buses.

Figure 5. MTBF for Hybrid and Diesel Buses



Mean Time Between Failures (MTBF) for conventional diesel buses and for hybrid diesel-electric buses (NYCT Operating Experience with Hybrid Transit Buses, APTA/EPRI/EVAA, John Lowell, New York City Transit, Electric Bus Workshop, October 10, 2002) (Reference 1)

Table 1. Mean Distance Between MDBF Data

Evaluation	CNG	Hybrid	Conventional diesel
Propulsion system MDBF (miles)	1549	541	4872
Chassis MDBF (miles)	581	1470	716
Total MDBF (miles)	443	429	696

Mean distance between failure (MDBF) data for the CNG, Hybrid, and Conventional Diesel buses evaluated in the San Francisco study program (San Francisco Municipal Railway, Fleet Engineering, Alternative Fuel Pilot Program; Initial 6 month Evaluation Results for 2 CNG 40-foot buses, 2 Hybrid/Electric 40-foot buses, 2 Clean Diesel w/PM filter 40-foot buses, 2 Clean Diesel control 40-foot buses; May, 2002) (Reference 4)

Figure 5 and Table 1, above, provide details from the NYCT and San Francisco Municipal Railway reports. However, please note that the reliability data for the hybrid diesel-electric buses is for the Orion/Lockheed Martin bus. This bus was the first such hybrid diesel-electric bus to be produced in substantial numbers, and should be regarded as a first generation model. The Allison/New Flyer bus that CTtransit™ will be operating and evaluating should be regarded as a second-generation model, with the expectation that it will have better operational characteristics, including reliability. This expectation is based in part on the second-generation nature of these buses. Additionally, the Allison/New Flyer hybrid bus and their conventional diesel bus have more sub-systems that are identical, whereas the sub-systems of the Orion/Lockheed Martin hybrid bus have much less commonality with those of the Allison/New Flyer conventional diesel bus.

For the NYCT hybrids, the lower reliability (and attendant higher maintenance costs) were attributed to the prototype nature of the buses, the inexperience of the depot mechanics, and the small number of hybrid buses relative to the total fleet. The lower reliability occurred across many systems, not just those involved in the propulsion system, perhaps in part because of the small number of buses. Reliability is expected to improve, and maintenance costs decline, as these issues are resolved. (Please see Ref. 1 for more detail.)

IV. BUS COST

The report from the San Francisco Municipal Railway, Fleet Engineering Department indicates that conventional diesel buses are still the least expensive buses to purchase. However, this report suggests that in contrast to the *BPT 2001* report, hybrid diesel-electric buses purchased in substantial quantity and CNG buses purchased in any quantity cost essentially the same. Also, as stated in the *BPT 2001* report, the infrastructure costs, although varying in detail, are greater (in some cases much greater) for CNG buses.

TABLE 2. PURCHASE COST FOR STANDARD 40-FOOT BUSES

Vehicle Propulsion Technology for standard 40-foot buses	Procurement Size	Cost per bus $K
Compressed natural gas (CNG)	Any	375-390
Hybrid diesel-electric	15	450-500
Hybrid diesel-electric	80 +	385-425
Diesel	Any	330
Diesel with PM filter	Any	340

Purchase cost for standard 40-foot buses, listed according to bus propulsion technology and by procurement size (San Francisco Municipal Railway, Fleet Engineering, Alternative Fuel Pilot Program; Initial 6 month Evaluation Results for 2 CNG 40-foot buses, 2 Hybrid/Electric 40-foot buses, 2 Clean Diesel w/PM filter 40-foot buses, 2 Clean Diesel control 40-foot buses; May, 2002) (Reference 4)

V. ALL-ELECTRIC BUSES

Two all-electric, or essentially all-electric, battery powered, buses with substantial range have appeared on the market since the earlier *BPT2001* report. These are:

- The Stingray, a high-temperature battery powered bus
- The Electric Fuel bus, a zinc/air battery powered bus

The Stingray is a bus that has been sponsored and developed by the Santa Barbara Electric Transportation Institute (SBETI). Although the present bus is a 30-foot bus (as compared to the CT DOT and CTTRANSIT™ standard 40-foot bus), it offers interesting features. It is truly an all-electric battery powered bus, and merits watching. The following comments are offered:

- The battery operates at a relatively high temperature, ~300 C, an operational consideration (however, thermal losses are reported to be modest).
- The present bus is limited in speed to about 48 mph (however, a 65 mph option is indicated).
- The present range is about 130 miles between recharges.
- Relatively rapid recharging (one mile of range per minute of charging) is straightforward.

A spokesman for the SBETI indicated that their experience with the bus has been very good, and that both drivers and riders were pleased.

However, a 40-foot version of this bus is not currently available, nor is their any indication of plans to produce a 40-foot version of the bus. Also, please note that the batteries, although substantially higher in energy density than competing systems, still weigh over 2,200 kg (~5,000 pounds) for the 30-foot bus, a substantial fraction of the 23,000 pound curb weight of the bus. For comparison purposes, the Detroit Diesel S40, a standard engine for 30-foot buses, weighs 635 kg (1,400 pounds).

Additional information regarding the Stingray bus is available on the SBETI website at: www.sbeti.com

The Electric Fuel bus is powered by an energy source that can be described either as a battery or as a fuel cell. However one describes it, the energy source for the Electric Fuel bus is a zinc/air cell, in which the zinc is converted to zinc oxide in the process of providing energy. The current developmental bus is a 40-foot bus, with a design range of 95 miles in a CBD cycle, with a future target range of over 100 miles for this cycle.

This bus technology is interesting in that the "recharge" cycle, which involves the change-out of the spent zinc oxide cartridge for a new zinc cartridge, can be rapid. However, the issues with this technology include:

- There is currently only one supplier for this propulsion system.
- The recharge cartridges must be returned to the manufacturer for recycling.
- The manual recharging procedure would be cumbersome with a substantial number of buses.
- The overall energy efficiency of the cycle is likely modest.

Despite these difficulties, the relatively high-energy storage density of this battery/fuel cell has attracted interest at the federal level, and Electric Fuel has recently been awarded contracts by the United States Federal Transit Administration (FTA) and the US Army Communications Electronic Command.

Additional information is available on the Electric Fuel website at www.electric.fuel.com.

SUMMARY OF FINDINGS

OVERVIEW

The current markets and findings are similar to those found in the earlier *Academy BPT2001* report. However, there are specific issues and developments that have occurred since the issuance of the *BPT2001* report that are of interest, as follows:

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Finally, it is recommended that Connecticut continue to monitor the development progress of all-electric buses.

REFERENCES

1. *NYCT Operating Experience with Hybrid Transit Buses*, John Lowell, New York City Transit Department of Buses, at the APTA/EPRI/EVAA Electric Bus Workshop, October 10, 2002. Similar information is also reported in *New York City Transit Diesel Hybrid-Electric Buses: Final Results*, Kevin Chandler, et al, a DOE/NREL Transit Bus Evaluation Project, July 2002, www.afdc.doe.gov.

2. *ARB's Study of Emissions from Two "Late-Model" Diesel and CNG Heavy-Duty Transit Buses*, Alberto Ayala et al, California Environmental Protection Agency, Air Resources Board, at the 12th CRC On-Road Vehicle Emissions Workshop, April 15-17, 2 002, San Diego, CA.

3. Allison Transmission Web Site, at www.allisontransmission.com. Please see also *California Air Resources Board, Heavy-Duty Emissions Laboratory Mobile Sources Control Division, Heavy-Duty Testing and Field Support Section, Test Engineers: Juan Osborn, Alvaro Gutierrez, Report 01-01, Test Dates 7/10/01 – 7/13/01.*

4. *Alternative Fuel Pilot Program, Initial 6 month Evaluation Results for 2 CNG 40-foot Buses, 2 Hybrid /Electric 40-foot Buses, 2 Clean Diesel w/PM filter 40-foot Buses, 2 Clean Diesel Control 40-foot Buses*, San Francisco Municipal Railway, Fleet Engineering, May, 2002.

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