Demonstration and Evaluation of Hybrid Diesel-Electric Transit Buses

A Report By

The Connecticut Academy of Science and Engineering

Executive Summary

Origin of Inquiry:	Connecticut Department of Transportation and CTTransit™
Date Inquiry Established:	August 23, 2005
Date Response: Released:	October 25, 2005

This study was initiated at the request of the Connecticut Department of Transportation and CTTransit™ on August 23, 2005. The project was conducted by an Academy Study Committee with the support of Academy Member George Foyt, ScD, Project Study Manager. The content of this report lies within the province of the Academy's Transportation Systems Technical Board. The report has been reviewed by Academy Members David E. Crow, PhD, Chairman, Transportation Systems Technical Board, Alan C. Eckbreth, PhD, Vice President/President Elect, and Jack Stephens, PhD. Martha Sherman edited the report. The report is hereby released with the approval of the Academy Council.

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Executive Director

Disclaimer

The contents of this report reflect the views of the author who is responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Connecticut Department of Transportation or the Federal Highway Administration. The report does not constitute a standard, specification, or regulation.

Technical Report Documentation Page

<table>
<tr><td>1.Report No.
CT-170-1884-F-05-10</td><td>2. Government Accession No.</td><td>3. Recipients Catalog No.</td></tr>
<tr><td colspan="2" rowspan="2">4. Title and Subtitle

Demonstration and Evaluation of Hybrid Diesel-Electric Transit Buses – Final Report</td><td>5. Report Date
October 2005</td></tr>
<tr><td>6. Performing Organization Code</td></tr>
<tr><td colspan="2">7. Author(s)
George Foyt</td><td>8. Performing Organization Report No.
CT-170-1884-F-05-10</td></tr>
<tr><td colspan="2" rowspan="3">9. Performing Organization Name and Address

Connecticut Academy of Science & Engineering
179 Allyn Street, Suite 512
Hartford, CT 06103-1422</td><td>10. Work Unit No. (TRIS)</td></tr>
<tr><td>11. Contract or Grant No.
CM-005984</td></tr>
<tr><td rowspan="2">13. Type of Report and Period Covered
Final Report
January 2001 – October 2005</td></tr>
<tr><td colspan="2" rowspan="2">12. Sponsoring Agency Name and Address
Connecticut Department of Transportation
2800 Berlin Turnpike
Newington, CT 06131-7546</td></tr>
<tr><td>14. Sponsoring Agency Code
170-1884</td></tr>
<tr><td colspan="3">15. Supplementary Notes
Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration. This project was funded primarily by a Congestion Mitigation Air Quality grant (CM-005984). The project partners were: CTTransit, Allison Transmission, Horiba Instruments, Inc., New Flyer Bus Industries, University of Connecticut, ConnDOT Bureau of Public Transportation, ConnDOT Division of Research, The East Coast Hybrid Consortium, and the Connecticut Academy of Science and Engineering.</td></tr>
<tr><td colspan="3">16. Abstract
The project goal was to identify the next generation of transit vehicles for future fleet replacement that are cost effective, reliable, produce fewer emissions, and have improved fuel economy compared to the standard heavy-duty diesel powered bus. Data was collected to produce an estimated life-cycle cost analysis, emissions information, mileage, fuel economy, power production, brake pad wear, and maintenance and repair costs. Bus operator and Customer surveys were also performed.

The 18 month project data collection effort was completed on December 31, 2004. The results found the hybrid buses to be very reliable and to achieve 10% better fuel economy than their comparable diesel buses. All vehicle emissions in the study were essentially the same. The hybrid buses had a lower life cycle cost when the current FTA 80% purchase subsidy was considered. The hybrid buses were rated very favorably by both the Bus Operators and Customers that rode in them.</td></tr>
<tr><td colspan="2">17. Key Words
Hybrid diesel electric, fuel economy, bus performance, emissions, battery, parallel</td><td>18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161</td></tr>
<tr><td>19. Security Classif. (Of this report)
Unclassified</td><td>20. Security Classif.(Of this page)
Unclassified</td><td>21. No. of Pages
52

20. Price</td></tr>
</table>

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

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LIST OF ACRONYMS

Acronym	Description
Base	Two late-model, conventional clean-diesel buses that were used as a standard of comparison for the two late-model, hybrid diesel-electric buses
BTU	British thermal units
CO_2	Carbon dioxide
CO	Carbon monoxide
DOC	Diesel oxidation catalyst (in the exhaust system)
DPF	Diesel particulate filter (in the exhaust system)
Fleet	The entire CTTransit bus fleet, except for the two base clean-diesel buses and the two hybrid diesel-electric buses that are the subject of this report
HC	Unburned hydrocarbons
Hybrid	Two late-model, hybrid diesel-electric buses that are the major subject of this report
MPG	Miles per gallon
NO_x	Oxides of nitrogen
Number 1	Number 1 diesel fuel (defined as having a sulfur content of less than 500 ppm. The fuel used in this program had a sulfur content that ranged from 230 to 320 ppm.)
PM	Particulate matter
PPM	Parts per million
ULSD	Ultra-low-sulfur diesel fuel (defined as having a sulfur content of less than 15 ppm. The fuel used in this program had a sulfur content that ranged from 8 to 51 ppm.)

EXECUTIVE SUMMARY

STUDY OBJECTIVES

The goal of this project is to identify for future fleet replacement the next generation of transit vehicles; these vehicles must have improved fuel economy, produce fewer emissions, and be cost effective and reliable when compared to the standard heavy-duty, clean-diesel powered bus.

SUMMARY OF FINDINGS

Two 2003-model-year, 40-foot, low floor New Flyer Allison hybrid diesel-electric buses, and two virtually identical 2002-model-year, 40-foot, low floor New Flyer standard clean-diesel buses (also identified as baseline, or base buses in this report) were tested in the course of this program. The hybrids and base buses were operated in virtually identical conditions on equivalent routes each day, duplicating revenue service in all cases. In all cases, the emissions were measured using on-board equipment. The testing program ended in December, 2004, for a total test period of 18 months.

To the best of the Study Committee's knowledge, this is the first time that emissions comparisons between a hybrid-electric bus and a similar conventional diesel bus have been made on-board the buses, on routes that represent in-service conditions. As such, this study offers a unique opportunity to evaluate real-world conditions for these transit buses.

Each bus was operated in three different situations. These were

- With conventional Number 1 diesel fuel and with a diesel oxidation catalyst (DOC) in the exhaust system
- With ultra-low-sulfur diesel fuel and with a DOC
- With ultra-low-sulfur diesel fuel and state-of-the-art exhaust gas treatment systems, including the addition of a diesel particulate filter (DPF) to the DOC

Key results of the program include the following:

- The hybrid buses demonstrated a slight improvement in fuel economy, compared to the base clean-diesel buses. Averaged over the entire test program, the improvement was about 10%.

- For any given fuel/exhaust gas treatment situation, the gaseous emissions (carbon dioxide, carbon monoxide, oxides of nitrogen, and unburned hydrocarbons) and particulate matter emissions were virtually identical for the hybrid buses and the base clean-diesel buses.

- For both bus types, the gaseous emissions and particulate matter emissions were essentially unaffected by the change to ultra-low-sulfur diesel fuel. In addition, the gaseous emissions were unaffected by the addition of the diesel particulate filter.

For both bus types, and in all cases, the particulate matter emissions were greatly reduced by the addition of the diesel particulate filter in the exhaust system. For particles in the size range of 10 nanometers to 130 nanometers — a size range of great current interest due to public health concerns — typical reductions were on the order of 99% (i.e., a 100 times reduction).

Fuel economy

The fuel economy of the hybrid buses, the base clean-diesel buses, and the rest of CTTransit's 397-bus fleet was measured in the course of this 18-month program. These tests included all the cases of the testing program: operation using Number 1 diesel fuel, operation using ultra-low-sulfur (ULSD) fuel, and operation using ULSD with the addition of a diesel particulate filter in the exhaust system. The resulting measurements are shown in Figure 1.

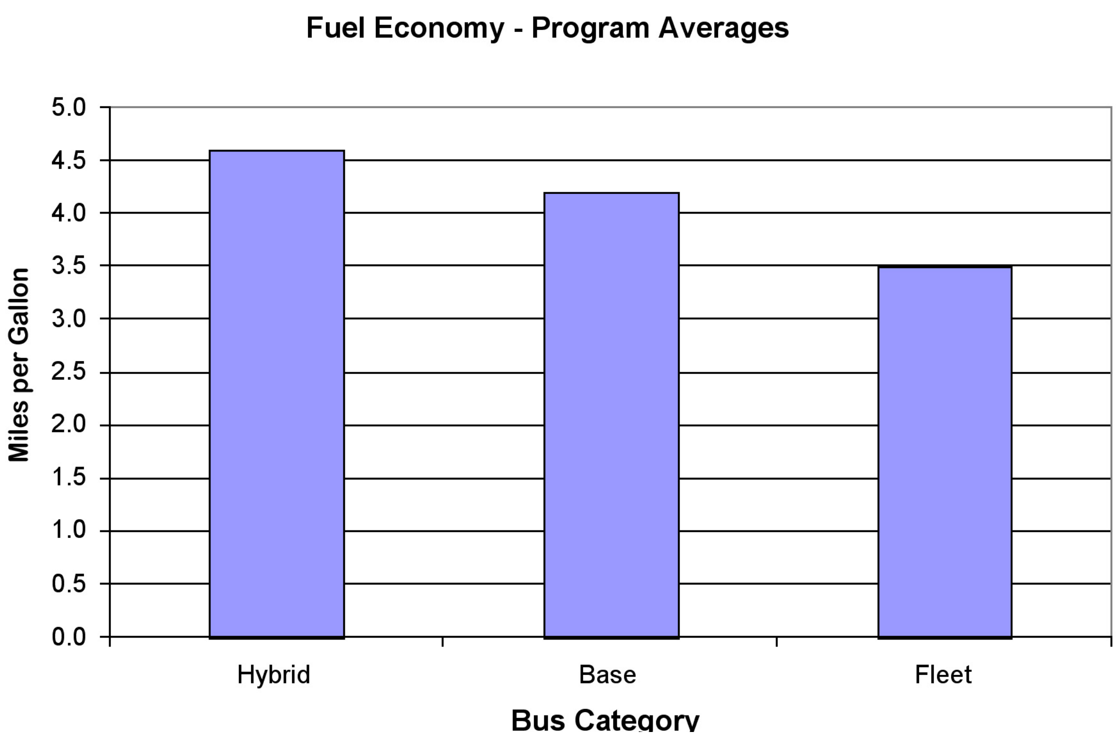

Figure 1: Average fuel economy, in miles per gallon (MPG), for the two hybrid buses tested in this program, the two base clean-diesel buses tested in this program, and the remainder of the CTTransit fleet. In all cases, the hybrids demonstrated the highest MPG, followed by the base clean-diesel buses, and then by the rest of the fleet.

Although not shown in this figure, there are seasonal variations in the fuel economy for all the bus types, with lower values in the summer and higher values in the winter. This variation is quite reasonable in view of the increased hotel load (air conditioning) required during the summer months.

During all months, the hybrids had the highest MPG, followed by the base clean-diesel buses and then by the rest of the fleet. Again, this result is quite reasonable in light of the fact that the hybrids and their conventional bus companions are of very recent designs (2003 and 2002), which represent improvements in engine design compared to the rest of the fleet.

Averaged over the entire test program, the hybrids demonstrated an improvement in fuel economy of about 10% over the base clean-diesel buses. This improvement is somewhat less than originally expected, and may be related to the details of the electrical power system. However, it is interesting to note that this modest improvement is very similar to that found in current hybrid electric-gasoline engine automobiles in which the same size engine is used in both hybrid and non-hybrid models of the same vehicle. (*Consumer Reports*, 2005, and *The New York Times*, 2005)

Gaseous emissions

The gaseous emissions — carbon dioxide, carbon monoxide, oxides of nitrogen (NO_x), and vunburned hydrocarbons — were measured on both the hybrid and base clean-diesel bus during operation on revenue service routes for CTTransit. In all cases, the measurements were made using on-board equipment, operated by experienced personnel from the University of Connecticut Department of Mechanical Engineering.

The revenue service routes for this program were chosen to represent the following types of service:

- Express bus, highway driving, point-to-point service. These are identified in the following figure as Enfield out (EO) and Enfield in (EI)
- Urban, frequent stop, city street service. These are Farmington out (FO) and Farmington in (FI)
- Service that was dominated by hill climbing. These are Avon out (AO up the mountain and AO down the mountain) and Avon in (AI up the mountain and AI down the mountain)

The results may be summarized very simply. *For all routes and for all fuel/exhaust systems, the results for the hybrid buses and for the base clean-diesel buses were virtually identical.*

By way of illustration, Figure 2 gives the average results for the entire program as measured when the buses were operated on number 1 diesel fuel and when they were fitted with a diesel particulate filter and operated on ultra-low-sulfur diesel fuel.

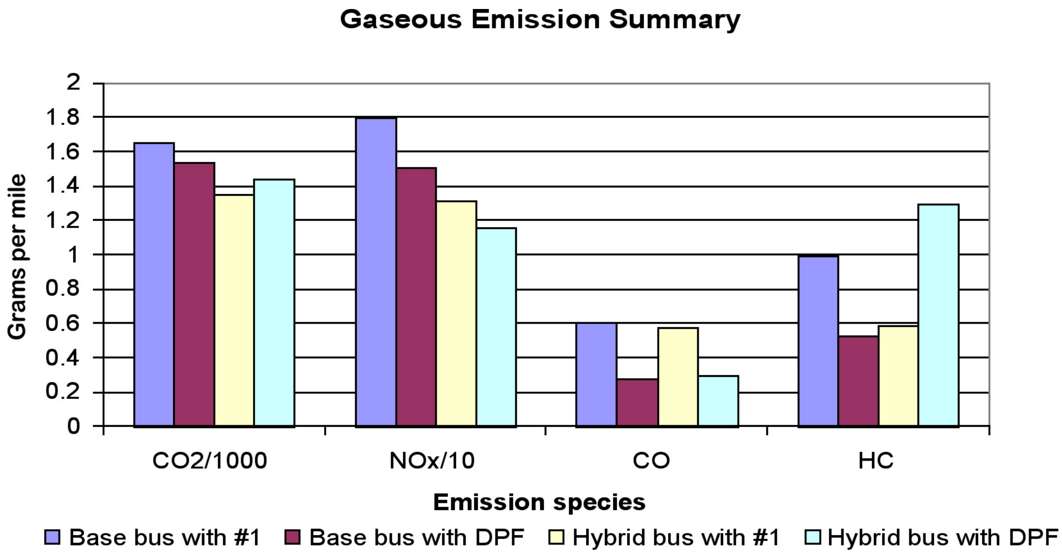

Figure 2. Summary of gaseous emissions (carbon dioxide, oxides of nitrogen, carbon monoxide, and unburned hydrocarbons) measured in this study. The four cases illustrated in the table include: the base clean-diesel buses operated on Number 1 diesel fuel; the same base buses operated on ultra-low-sulfur-diesel (ULSD) fuel and fitted with diesel particulate filters (DPF); the hybrid buses operated on Number 1 diesel fuel, and the hybrid buses operated on ULSD fuel and fitted with DPFs. Please note the different scales on each of the four species measured (from Cetegen, et al, 2005, on the CD).

It should be noted that the results of other studies (see, for example Ayala, 2002), which found that the emissions of CO and HC are reduced with the addition of a DPF to the exhaust system, are not reproduced here. This may be due to the small values of these compounds in the exhaust of these modern buses or to the actual on-road testing conditions.

Particulate emissions

The particulate emissions (PM, both total mass and number distribution) were measured on both the hybrid and base clean-diesel buses during operation on revenue service routes for CTTransit. In all cases, the measurements were made using on-board equipment, operated by experienced personnel from the University of Connecticut Department of Civil and Environmental Engineering. These measurements were made concurrently with the gaseous emissions measurements noted above.

As for the gaseous emissions, the PM results may be summarized very simply: for a given route and for all fuel/exhaust system configurations, the results for the hybrid buses and for the base clean-diesel diesel buses were virtually identical.

However, unlike the gaseous emission results, there was a very large reduction in the particulate emissions when the buses were fitted with diesel particulate filters and operated on ultra-low-sulfur fuel.

To illustrate this reduction, we focus on the results for the Farmington Avenue route, a route typical of urban service. The data are shown in Figure 3.

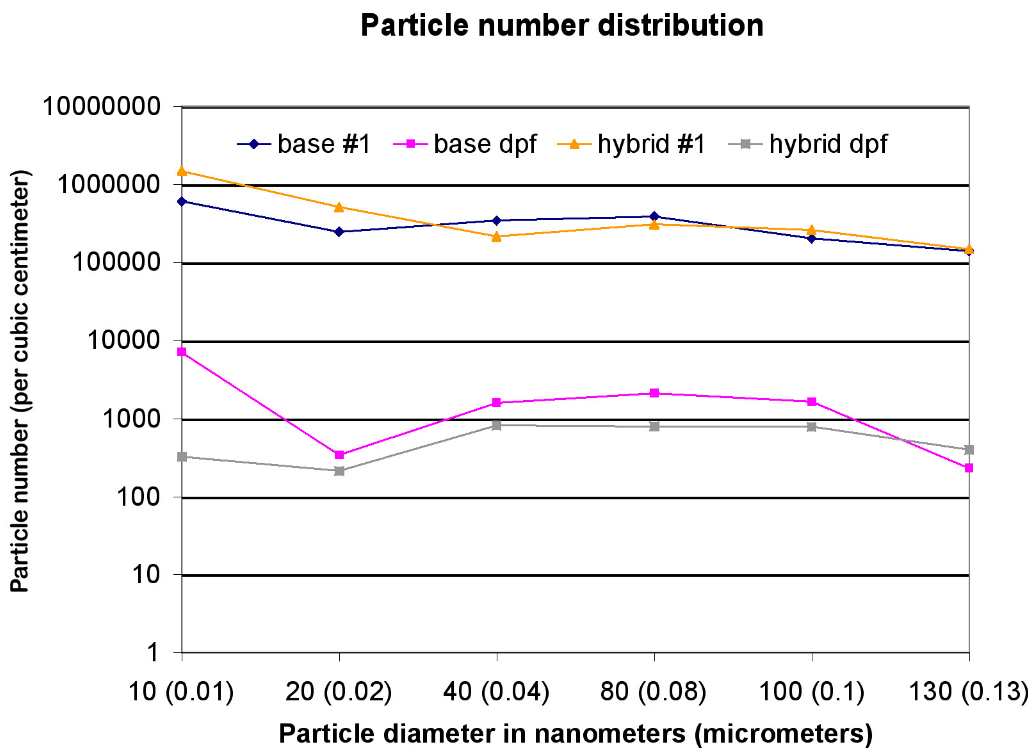

Figure 3: Particle number concentrations for the hybrid buses and the base clean-diesel buses on the Farmington Avenue route. The two cases shown are for bus operation using Number 1 diesel fuel and for operation with the bus fitted with a diesel particulate filter and using ultra-low-sulfur diesel fuel. The results for both bus types are nearly identical. In both cases, the particle number concentrations are reduced by 99% (i.e., a factor of 100) by the use of the DPF. This reduction occurs over the entire particle size range shown in these charts, from 10 nm to 130 nm (0.01 to 0.13 micrometer). (Holmén, et al, 2005, on the CD)

Dimensions on the order of 10 to 100 nanometers are difficult to visualize. However, for comparison, the diameter of a human hair is about 100 micrometers, and 100 nanometers is one thousand times smaller than 100 micrometers.

Reliability

The reliability of both the hybrid buses and the base clean-diesel buses has been very good — considerably better than the averages for the rest of the CTTransit fleet. In particular, the Miles-between-Road-Calls have been substantially higher (about 12,000 miles, 10,000 miles, and 4,000 miles respectively, for the hybrid, base, and fleet buses), and the Maintenance-Costs-per-Mile have been substantially lower.

Driver and rider surveys

Drivers and riders alike prefer the hybrid buses. The drivers liked the greater acceleration from a stop for the hybrids, while the riders liked the lower noise and vibration for the hybrids.

Cost

Based on current information and on projections of fuel and maintenance costs, the total life-cycle cost of ownership for the hybrid bus is estimated to be substantially higher than that for the conventional clean-diesel bus (~$880K vs. $751K), whereas the total life-cycle costs to

Connecticut for the hybrid bus are somewhat lower (~$480K vs. $495K) based on the current federal subsidy of 80% of the bus purchase price.

CONCLUDING REMARKS

As discussed in more detail in Chapter VI, Summary of Findings and Concluding Remarks, both the hybrid buses and the base clean-diesel buses are welcome additions to the CTTransit fleet. The emissions performance has been outstanding for both bus types when fitted with diesel particulate filters and operated on ultra-low-sulfur diesel fuel, especially for reduced particulate emissions. Each bus type has advantages and limitations. For the hybrids, as compared to the conventional buses, the advantages include somewhat better fuel economy, lower noise and vibration, lower expected maintenance costs, and greater rider and driver preference. For the conventional buses, the advantages include considerably lower purchase cost and a history of reliable and dependable operation.

On the basis of this study, the Study Committee recommends that CTTransit should continue to purchase conventional state-of-the-art diesel buses, fitted with state-of-the-art exhaust systems and operated on ultra-low-sulfur diesel fuel. Additonally, CTTransit should consider the purchase of additional hybrid buses of newer and different designs in study quantities, to help in understanding whether (or not) the expected inherent advantages of a hybrid design will be realized. If the results for these newer buses are positive, consider the purchase of still larger quantities of hybrid buses. In particular, the committee suggests that designs with smaller engines and larger battery packs be considered, with the likely possibility that these changes will result in improved fuel economy, and perhaps lower life-cycle cost.

CD INCLUDED WITH THIS REPORT

On the back cover of this report, there is a CD, which contains the following:

- *Demonstration and Evaluation of Hybrid Diesel-Electric Transit Buses* (this report)
- *CTransit Hybrid and Conventional Bus Gas Emission Measurement Test Report,* prepared by Baki M. Cetegen, PhD; Professor, Department of Mechanical Engineering, University of Connecticut (includes extensive appendices, detailing the gaseous emissions testing program and results)
- *Particulate Matter Emissions From Hybrid Diesel-Electric and Conventional Diesel Transit Buses: Fuel and Aftertreatment Effects,* prepared by Britt A. Holmén, PhD; Professor, Department of Civil and Environmental Engineering, University of Connecticut (includes extensive appendices, detailing the particulate matter emissions testing program and results)