Demonstration and Evaluation of Hybrid Diesel-Electric Transit Buses

October, 2005

A Report By

The Connecticut Academy of Science and Engineering

Connecticut Academy of Science and Engineering

Qui Transtulit Sustinet

1976

For

The Connecticut Department of Transportation and CTTransit™

Demonstration and Evaluation of Hybrid Diesel-Electric Transit Buses

A Report By

The Connecticut Academy of Science and Engineering

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.

Richard H. Strauss
Executive Director

Disclaimer

Technical Report Documentation Page

1.Report No. CT-170-1884-F-05-10	**2. Government Accession No.**	**3. Recipients Catalog No.**
4. Title and Subtitle Demonstration and Evaluation of Hybrid Diesel-Electric Transit Buses - Final Report		**5. Report Date** October 2005 **6. Performing Organization Code**
7. Author(s) George Foyt		**8. Performing Organization Report No.** CT-170-1884-F-05-10
9. Performing Organization Name and Address Connecticut Academy of Science & Engineering 179 Allyn Street, Suite 512 Hartford, CT 06103-1422		**10. Work Unit No. (TRIS)** **11. Contract or Grant No.** CM-005984 **13. Type of Report and Period Covered** Final Report January 2001 - October 2005
12. Sponsoring Agency Name and Address Connecticut Department of Transportation 2800 Berlin Turnpike Newington, CT 06131-7546		**14. Sponsoring Agency Code** 170-1884

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.

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.

17. Key Words Hybrid diesel electric, fuel economy, bus performance, emissions, battery, parallel	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (Of this report)	**20. Security Classif.(Of this page)**	**21. No. of Pages**	**20. Price**
Unclassified	Unclassified	52	

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

CTTRANSIT PROJECT MEMBERS DEMONSTRATION AND EVALUATION OF HYBRID DIESEL-ELECTRIC TRANSIT BUSES

Stephen Warren *(Project Manager)*
John Warhola *(Research Team Leader)*

Technical Adviser Committee

Stephen Warren *(CTTRANSIT)*
John Warhola *(CTTRANSIT)*
Dennis Jolly *(ConnDOT Bureau of Public Transportation)*
James Sime *(ConnDOT Division of Research)*
George Foyt *(CASE)*
Joe Ambrosio *(Odyne)*

Bus Gas Emissions UCONN Research Team

Baki M. Cetegen *(Professor & Principal Investigator)*
Andres Chaparro *(Research Assistant)*
Eric Landry *(Research Assistant)*

Bus Particulate Matter Emissions UCONN Research Team

Britt A Holmén *(Professor & Principal Investigator)*
Zhong Chen *(Research Assistant)*
Aura C. Davila *(Research Assistant)*
Oliver Gao *(Research Assistant)*
Jason Lewandowski *(Research Assistant)*
Derek M. Vikara *(Research Assistant)*

MEMBERS OF THE CONNECTICUT ACADEMY OF SCIENCE AND ENGINEERING STUDY COMMITTEE ON DEMONSTRATION AND EVALUATION OF HYBRID DIESEL-ELECTRIC TRANSIT BUSES

Alberto Ayala, PhD,
Manager of Emission Control Technology Research, Research Division
California Air Resources Board
California Environmental Protection Agency

Gale Hoffnagle *(Academy Member)*
Senior Vice President & Technical Director
TRC Environmental Corporation

Herbert Levinson *(Academy Member)*
Transportation Consultant
Professor of Civil Engineering
University of Connecticut (ret.)

Fred Robson, PhD
Consultant, Principal Engineer
kraftWorks Systems, Inc.

Joseph Sangiovanni, PhD
Senior Research Fellow
United Technologies Research Center

Research Team

Study Manager
George Foyt, ScD *(Academy Member)*
Consultant
Foyt & Associates

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.

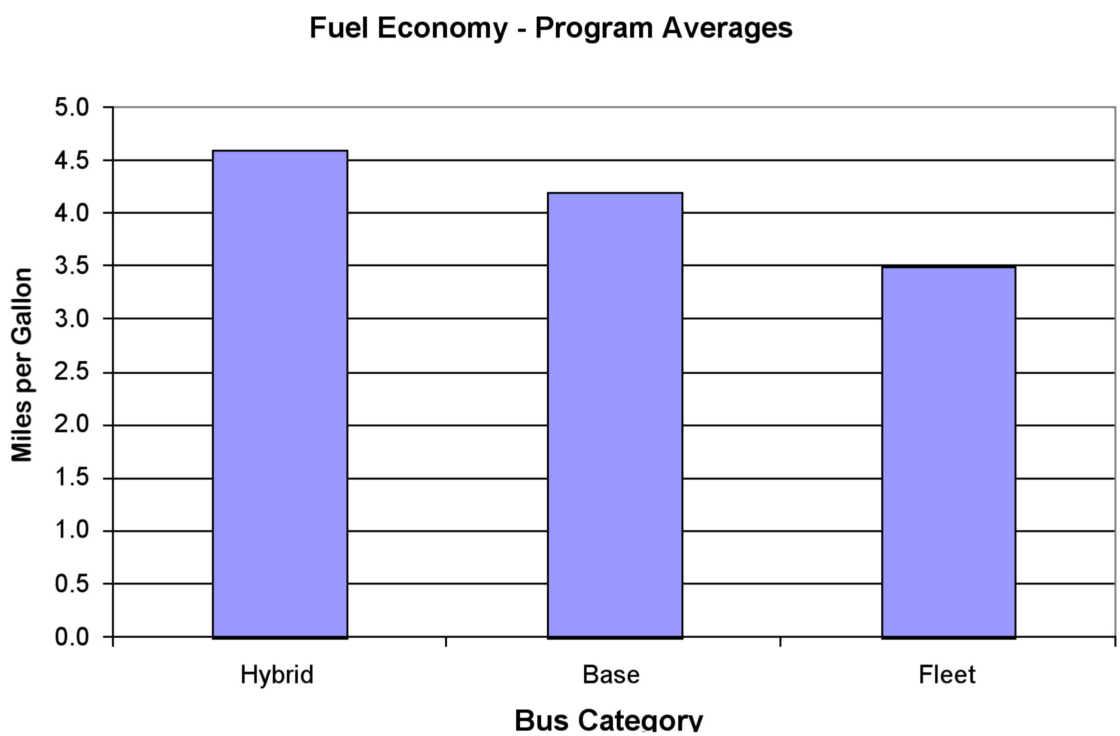


Figure 1: Average fuel economy, in miles per gallon (MPG), for the two hybrid buses tested in this program, the two base clean-diesel buses tested in this program, and the remainder of the CTTransit fleet. In all cases, the hybrids demonstrated the highest MPG, followed by the base clean-diesel buses,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

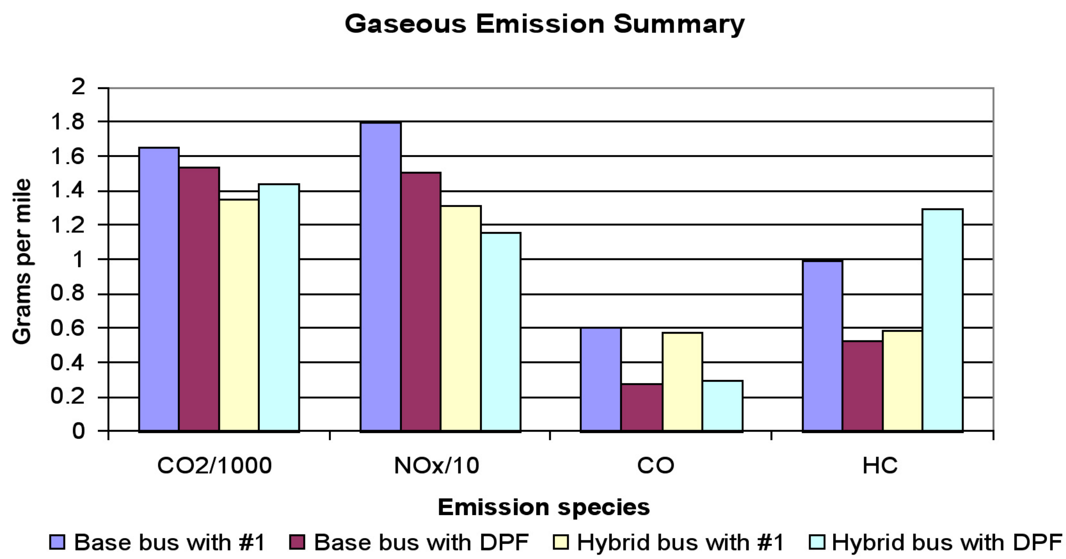


Figure 2. Summary of gaseous emissions (carbon dioxide, oxides of nitrogen, carbon monoxide, and unburned hydrocarbons) measured in this study. The four cases illustrated in the table include: the base clean-diesel buses operated on Number 1 diesel fuel; the same base buses operated on ultra-low-sulfur-diesel (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.

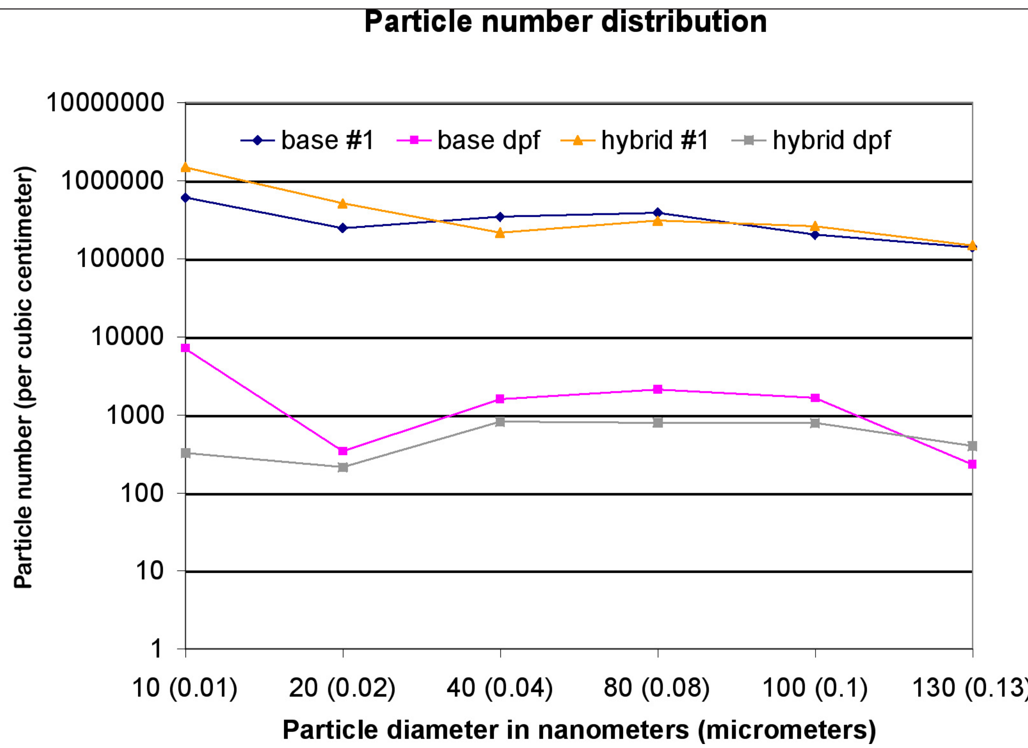


Figure 3: Particle number concentrations for the hybrid buses and the base clean-diesel buses on the Farmington Avenue route. The two cases shown are for bus operation using Number 1 diesel fuel and for operation with the bus fitted with a diesel particulate filter and using ultra-low-sulfur diesel fuel. 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)

TABLE OF CONTENTS

I. INTRODUCTION AND BACKGROUND

The goal of this project is to identify, for CTTransit's 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 standard heavy-duty, clean-diesel powered bus.

BUSES TESTED

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 diesel buses (baseline, or base buses in this report) were tested in the course of this program. Table 1 below lists several of the important parameters for these buses.

Specification	**Hybrid-Electric Diesel (HED)**	**Conventional Clean-Diesel (CD)**
Engine	Cummins ISL	Detroit Diesel Series 40E
Transmission	Allison E^{P} 40	Allison B400R Automatic
Rated Power @ 2000 RPM, bhp (kW)	289 (205)	280 (205)
Peak Torque, lb-ft (N-m)	900 (1220)	900 (1166)
Combustion/Fuel System	Electronic Timing Control	Direct Injection
# cylinders, displacement (L)	6 cyl., 8.9 L	6 cyl., 8.7 L
Compression Ratio	16.6:1	17.2:1
Aspiration	Turbocharged, Charge Air Cooled	Turbocharged Air-to-Air Cooled
Emissions Certification	2001 EPA/ CARB	Certified through Dec. 31, 2003
EGR System	None	None
Exhaust Aftertreatment	Oxidation catalyst/diesel particulate filter by project phase	Oxidation catalyst/diesel particulate filter by project phase
Weight, kg	13,318	13,086
Size (L x H x W), m	12.19 x 3.32 x 2.59	12.19 x 2.82 x 2.59
Seats	38	38
Electric motors	Two Concentric AC Induction Motors	N/A
Battery	Sealed Nickel-Metal Hydride	N/A
Bus mileage prior to testing, mi	29,600 (H301); 28,800 (H302)	78,400 (201); 67,000 (202)
Bus mileage after testing, mi	56,300 (H301); 49,500 (H302)	111,500 (201); 102,700 (202)

* Information obtained from Detroit Diesel Series 40 specifications for urban bus, Cummins ISL data sheet and CTTransit comparison chart.

Table 1 - important parameters of the buses (Holmén, 2005)

TEST PROGRAM

The test program was divided into two broad categories.

The first category, conducted by CTTransit, consisted of a detailed tracking of bus performance over the entire 18-month test program. The parameters tracked included:

- fuel usage (total fuel divided by total miles for each bus in the 18-month program)
- oil usage (total oil divided by total miles for each bus in the 18-month program)
- mean time between road calls
- maintenance costs

The second category, conducted by personnel from the University of Connecticut, consisted of periodic measurement of bus exhaust emissions. The emissions that were measured were:

- gaseous emissions (carbon dioxide, carbon monoxide, oxides of nitrogen, and unburned hydrocarbons), and
- particulate matter, including both total particulate mass and a detailed measurement of the size distribution of the particles

All the exhaust emission measurements were made with on-board equipment, with the buses operated over standard CTTransit routes (see below). *The study committee believes that this is the first time that such in-service, mobile measurements have been performed to compare hybrid diesel-electric buses and conventional diesel buses on in-service routes.*

Table 2 on the following page provides detail for the emissions testing of each bus.

Date	Conventional Diesel		Hybrid		Test phase
	Bus 201	Bus 202	Bus 301	Bus 302	
01/06/04			X		Initial test
01/21/04			X		Initial test
01/23/04	X				Initial test
01/30/04	X				Initial test
02/11/04		X			Initial test
02/13/04		X			Initial test
02/18/04		X			Initial test
02/27/04				X	Initial test
04/16/04			X		#1 diesel
04/21/04			X		#1 diesel
04/23/04	X				#1 diesel
04/27/04		X			#1 diesel
04/30/04				X	#1 diesel
05/26/04		X			#1 diesel
05/27/04		X			#1 diesel
06/29/04		X			ULSD
07/29/04			X		ULSD
08/03/04			X		ULSD
08/04/04			X		ULSD
08/04/04	X				ULSD
08/10/04	X				ULSD
08/25/04				X	ULSD
08/26/04				X	ULSD
09/20/04		X			ULSD
09/21/04		X			ULSD
10/13/04			X		ULSD/DPF
10/15/04			X		ULSD/DPF
10/20/04	X				ULSD/DPF
10/25/04	X				ULSD/DPF
11/02/04				X	ULSD/DPF
11/03/04				X	ULSD/DPF
11/09/04		X			ULSD/DPF
11/10/04		X			ULSD/DPF
11/16/04			X		ULSD/DPF
11/17/04			X		ULSD/DPF

Table 2: Dates of emission testing for each bus in this program. There were four phases of this testing program: (1) an initial phase, in which the equipment was installed and modified as needed to ensure reliable testing in the remaining phases; (2) testing with Number 1 diesel fuel and a DOC; (3) testing with ultra-low-sulfur diesel fuel and a DOC; and (4) testing with ultra-low-sulfur diesel fuel with a DOC and a diesel particulate filter. (Cetegen, 2005)

ROUTES

Three CTTRANSIT bus routes were selected, representing

- high-speed steady-state freeway cruise on a commuter route (Enfield)
- start-stop activity on a local city street with frequent bus stops (Farmington)
- a combination of steady-state arterial travel with a high-grade section (Avon)

The routes are shown below in Table 3.

Route	**Enfield**		**Farmington**		**Avon**	
Route type	Freeway		Local stop-start		Arterial w/grade	
In bound/outbound	IN	OUT	IN	OUT	IN	OUT
Distance (mi)	16.4	16.4	5.2	5.2	8.2	8.2
Average Speed (mi/hr)	59.3	58.4	9.8	10.3	35.4	35.7
Number of Stops	1	1	23	21	1	1
Average Percent Load	72	78	41	42	48	55
Max/Min Acceleration Rate (mph/s)	2.3/-4.0	2.8/-3.6	5.5/-4.3	5.5/-4.2	10.5/-16.1	8.3/-12.5
Max/Min Grade (%)	3.1/-5.6	4.1/-3.3	5.6/-6.7	6.9/-5.3	8.99/-8.66	8.41/-9.15
Average % Idle Time	0.5	1.0	34.3	33.4	6.6	5.8

Table 3: Details of the test routes (Holmén, 2005)

The following sections of this report deal with

- Fuel Economy (II)
- Emissions (III)
- Reliability, Performance, and Surveys (IV)
- Cost (V)
- Summary of Findings and Concluding Remarks (VI)

II. FUEL ECONOMY

The fuel economy/fuel usage was measured for the entire CTTransit fleet during the period of this program, July, 2003 to December, 2004. The fuel economy was determined by measuring the total mileage driven by each bus during the course of the program, and dividing that mileage by the total fuel consumed for each bus. In all cases, all the buses were operated on a variety of different routes, to ensure that the comparisons were meaningful. The results of this 18-month evaluation are shown in Figures 4 and 5.

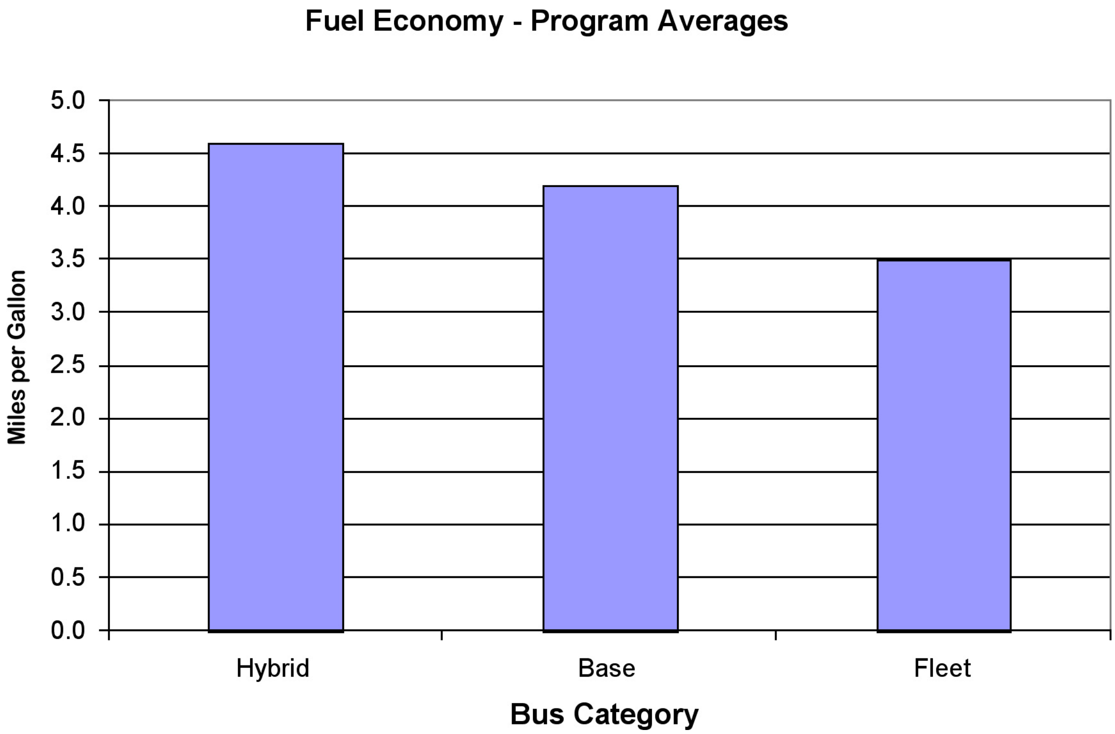


Figure 4: Average fuel economy, in miles per gallon (MPG), for the two hybrid buses tested in this program, the two base clean-diesel buses tested in this program, and the remainder of the CTTransit fleet. In all cases, the hybrids demonstrated the highest MPG, followed by the base clean-diesel buses, and then by the rest of the fleet.

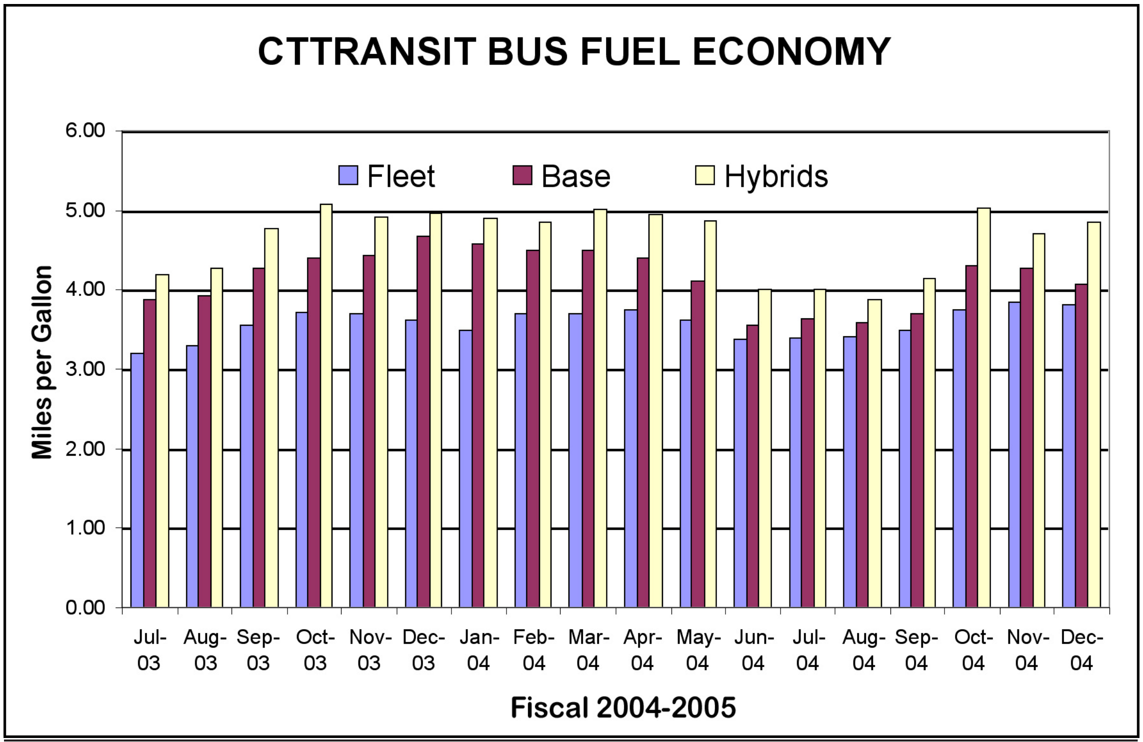


Figure 5: Fuel economy/fuel usage, in miles per gallon (MPG), as measured on a monthly basis, for the hybrid buses, the base clean-diesel buses, and the remainder of the 397-bus CTTransit fleet. During every month of the program, the hybrids had the highest MPG, followed by the base buses, and then the remainder of the fleet.

As Figure 5 indicates, there are seasonal variations in the fuel economy for all 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. This result is quite reasonable because the hybrids and their base bus companions are very recent (2003 and 2002) designs, which represent improvements in engine design compared to the rest of the fleet.

Fuel economy values did not seem to be affected by the changes in type of fuel or changes in the exhaust gas treatment system (that is, with and without the diesel particulate filter).

- From the start of the program (July, 2003) until May, 2004, Number 1 diesel fuel was used.
- From June, 2004 until September, 2004, ultra-low-sulfur (ULSD) diesel fuel was used. (Please note that the apparently lower fuel economy for this study period is almost certainly due to the increased hotel load (air conditioning) during these summer months.)
- From October, 2004, until the end of the program in December, 2004, ULSD was used, and diesel particulate filters (DPF) were added to the exhaust gas systems.

These results are quite understandable because the energy content of the two fuels was virtually identical, at 134,000 ± 1,500 BTU/gallon.

Finally, averaged over the entire test program, the hybrids demonstrated an improvement of about 10% in fuel economy compared to 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 (i.e., a relatively modest size battery and relatively modest exercise of this battery during bus operation). 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 versions of the same model. (*Consumer Reports*, 2005, and *The New York Times*, 2005)

III. EMISSIONS

A major component of this program was the measurement of exhaust emissions from the two hybrid buses and the two base clean-diesel buses. To approximate real-world, in-service measurements, techniques and instruments were developed to allow these measurements to be made while the buses were in simulated revenue service routes on CTTransit routes. This section will describe some elements of those techniques and instruments and a sampling of the results.

There are extensive reports on this emissions measurement program available on the CD version of this report. In particular, Professor Baki M. Cetegen and his colleagues, of the University of Connecticut Mechanical Engineering Department, delivered a 25-page report (with extensive appendices) to CTTransit on the gaseous emissions program, and Professor Britt A. Holmén and her colleagues, of the University of Connecticut Department of Civil and Environmental Engineering, delivered a 53-page report (also with extensive appendices) to CTTransit. All the data shown below are drawn from those reports. Also, all of the photographs shown below are taken from those two reports.

The Study Committee was concerned that the data in this section might be influenced by the aging of the DPF. However, this is not apparently the case. It is well known in the community that DPFs are very active in the early part of their operation, which early activity might affect the results. We were assured by CTTransit that each DPF had been operated for at least 2,000 miles, a time sufficient to minimize this early phase.

The Study Committee would have liked for some more details of the DPF. However, as of this report, these details are not available from the supplier.

SUITE OF INSTRUMENTS

The instruments that were developed to perform these emission measurements, and the additions to the buses that were made, included the following:

- a tailpipe extension to the bus exhaust system, to enable sampling of the bus exhaust in a more nearly laminar flow condition
- an auxiliary, trailer-mounted generator and air compressor, to provide power to instruments without disturbing the bus configuration and deliver dilution air for the particle measurements
- an extensive array of piping and tubing to transfer the sampled bus exhaust to the measuring equipment
- an integrated gas analyzer module that measures carbon dioxide, carbon monoxide, the oxides of nitrogen, and unburned hydrocarbons in the exhaust system
- three separate instruments for measuring the particulate matter in the bus exhaust system

Although it is very difficult to capture the technical challenges faced in this program, in pictures, the next several figures provide an overview of the on-board sampling equipment.

Figure 6: Photograph of the exhaust pipe extension that enabled sampling of the bus exhaust under near laminar flow conditions

Figure 7: Photograph of the interior of a bus under test, illustrating some of the piping and tubing that was needed to transfer the sampled bus exhaust to the several measuring instruments

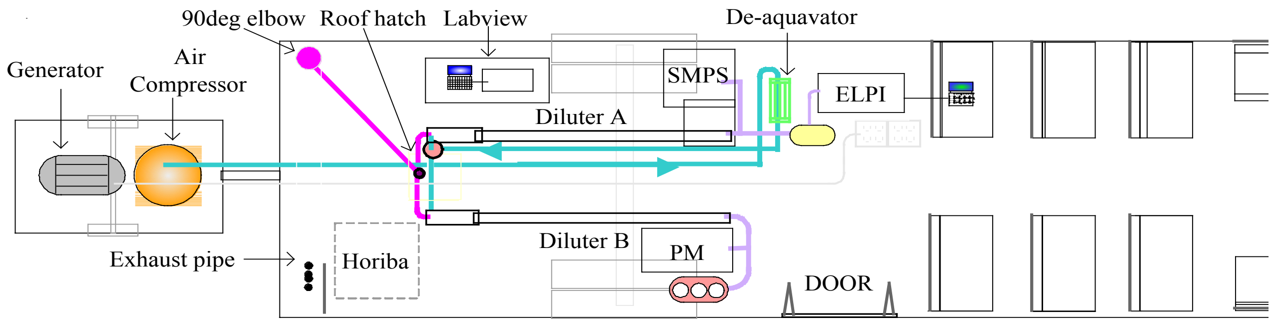


Figure 8: Sketch illustrating the overall test configuration, including the exterior generator and air compressor, the Horiba gas analyzer, and the three stations for measuring particulate matter (PM, SMPS, and ELPI). Note that all of this equipment is mounted on, or attached to, the bus, enabling in-service measurements.

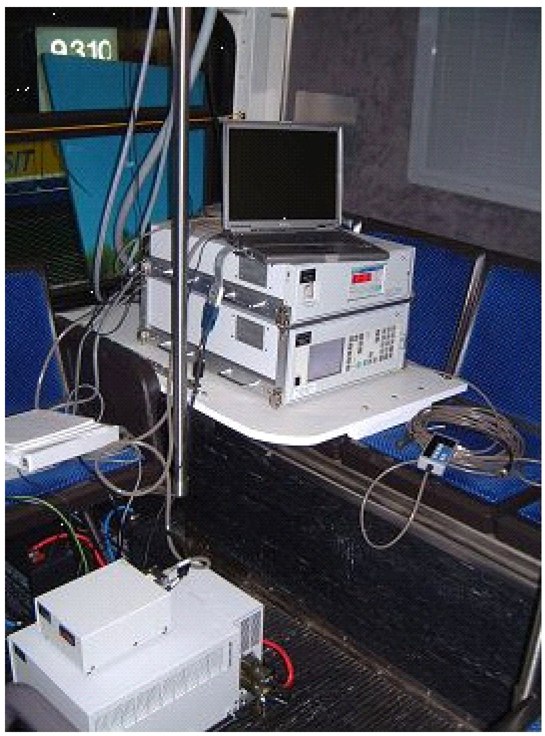


Figure 9: Photograph of the Horiba gaseous species measuring equipment

Figure 10: Photograph of the SMPS particle number concentration instrument

Gaseous emissions

The gaseous emissions were measured in the course of this program, as discussed above and in the introduction. As an overall comment, these test results indicate no discernible differences between the hybrid and conventional diesel buses in terms of the CO_2 and NO_x mass emissions for all test routes. Both types of buses exhibited higher CO and hydrocarbon emission on the city route with many stops as compared to the other two routes with higher speed and steep grades. The variation of the results during these tests indicated that CO_2 and NO_x emission measurements were repeatable within 10%, while a higher degree of variability was observed for the CO and hydrocarbon emissions. (See Cetegen, et al, 2005, on the CD for an extensive discussion of these measurements)

Figure 11 gives the results for all four species measured (carbon dioxide, carbon monoxide, unburned hydrocarbons, and the oxides of nitrogen), averaged over all of the tests.

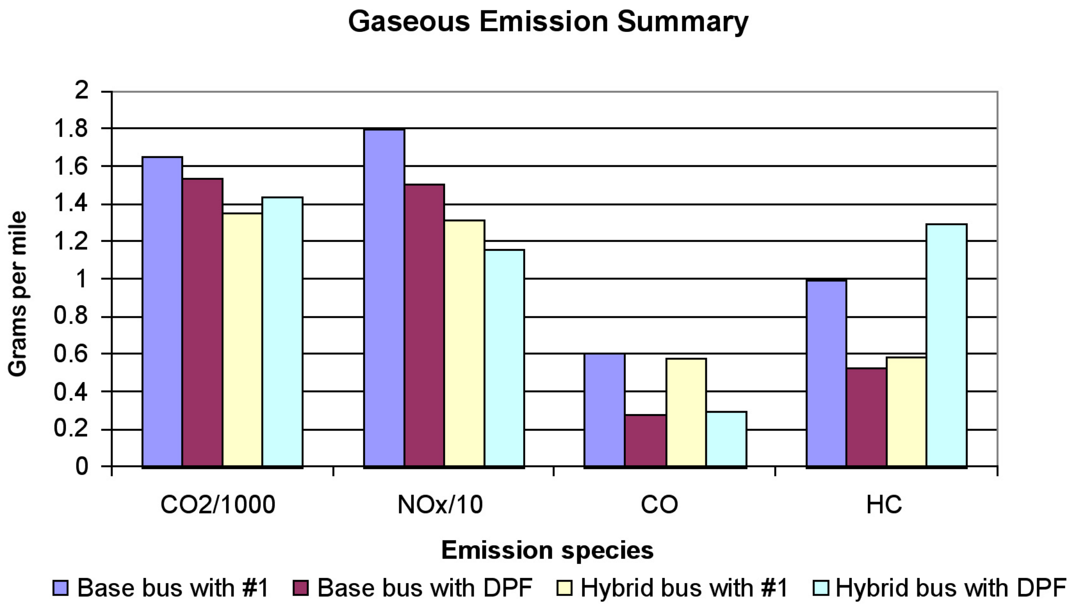


Figure 11: Summary of gaseous emissions (carbon dioxide, oxides of nitrogen, carbon monoxide, and unburned hydrocarbons) measured in this study. The four cases illustrated in the table include: the base clean-diesel buses operated on Number 1 diesel fuel; the same base buses operated on ultra-low-sulfur-diesel (ULSD) fuel and fitted with diesel particulate filters (DPFs); 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).

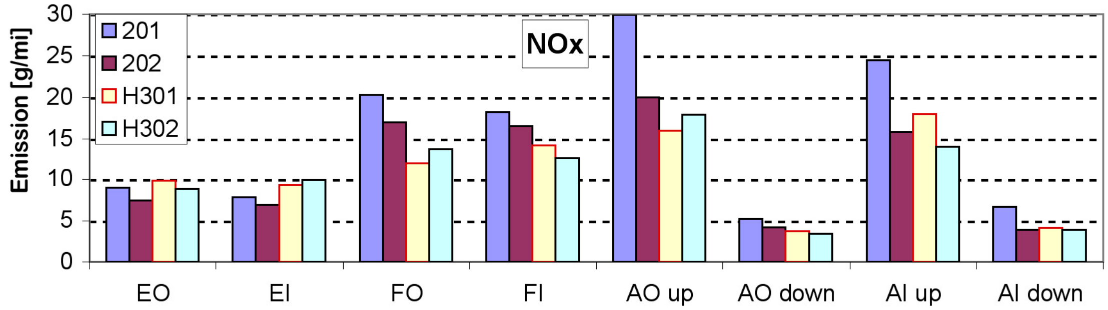
For the emissions that were well above the limits of measurement, CO and NO_x, there were slight reductions for the hybrid buses as compared to the base buses. The CO reductions (about 10%) are roughly consistent with the improved fuel economy of the hybrid buses. The slight NO_x reductions may be an indication that the diesel engines in these hybrid buses are operated in a somewhat more favorable mode, with less demand at low speeds and initial bus acceleration.

For the emissions that were near the limits of measurement, CO and HC, there were no clear-cut differences in the emissions for the hybrid buses and the base buses. The Study Committee did not find this result surprising, in view of the low levels of emission (~ 1 gram/mile or less) and the substantial variation in the test-to-test results for these modern buses.

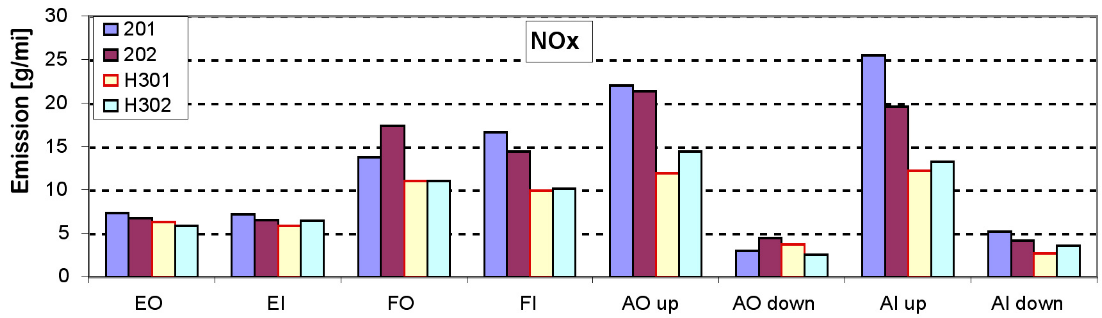
However, it is important to note that the results of other studies (see, for example Ayala, 2002), found that the emissions of CO and HC are reduced with the addition of a DPF to the exhaust system. These different results may be due to the small values of these compounds in the exhaust of these modern buses or to the actual on-road testing conditions.

As noted above, the average gaseous emissions from the hybrid buses, under all of the fuel/exhaust system combinations, were very similar to those from the base clean-diesel buses. To further illustrate these points, the results for the oxides of nitrogen are summarized on the following page, in Figure 12.

NO_x MEASUREMENTS WITH THE BUSES OPERATED ON NUMBER 1 DIESEL FUEL



NO_X MEASUREMENTS WITH THE BUSES OPERATED ON ULTRA-LOW-DIESEL-FUEL



NO_X MEASUREMENTS WITH THE BUSES FITTED WITH DIESEL PARTICULATE FILTERS AND OPERATED ON ULTRA-LOW-DIESEL-FUEL

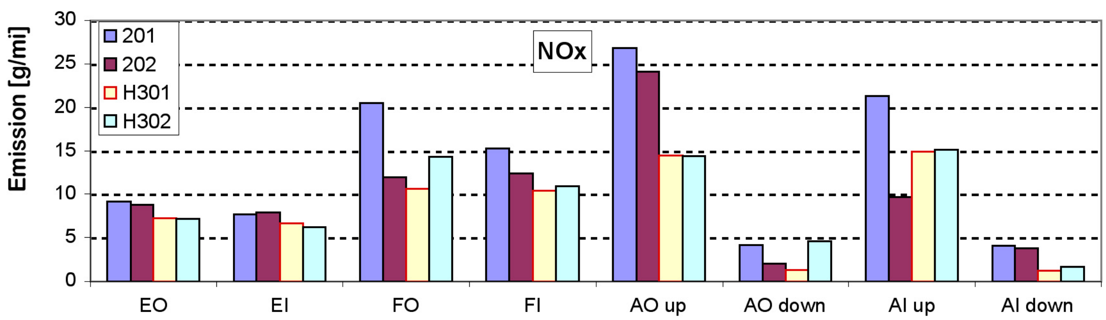


Figure 12: Charts illustrating the measured average values of the oxides of nitrogen for all the routes used in this program, and for all three fuel/exhaust system configurations. The routes are Enfield (EO out and EI in), Farmington Avenue (FO out and FI in), and Avon Mountain (AO up the hill, AO down the hill, AI up the hill, and AI down the hill) The fuel/ exhaust system conditions are: Number 1 diesel fuel (top chart), ultra-low-sulfur diesel-fuel (ULSD) (middle chart), and ULSD with a Diesel Particulate Filter in the exhaust system (lower chart)

Particulate Emissions

The particulate exhaust emissions were measured in several ways during the program. (See Holmén, et al, 2005, on the CD for an extensive discussion of these measurements.)

In the Executive Summary, the measurement that counted particle distribution as a function of particle diameter was shown, illustrating the dramatic reduction in number for the particle range of 10 nm to 130 nm (0.01 to 0.13 micrometers) that was achieved with the addition of a diesel particulate filter (DPF) to the exhaust system. This chart is repeated here, as Figure 13.

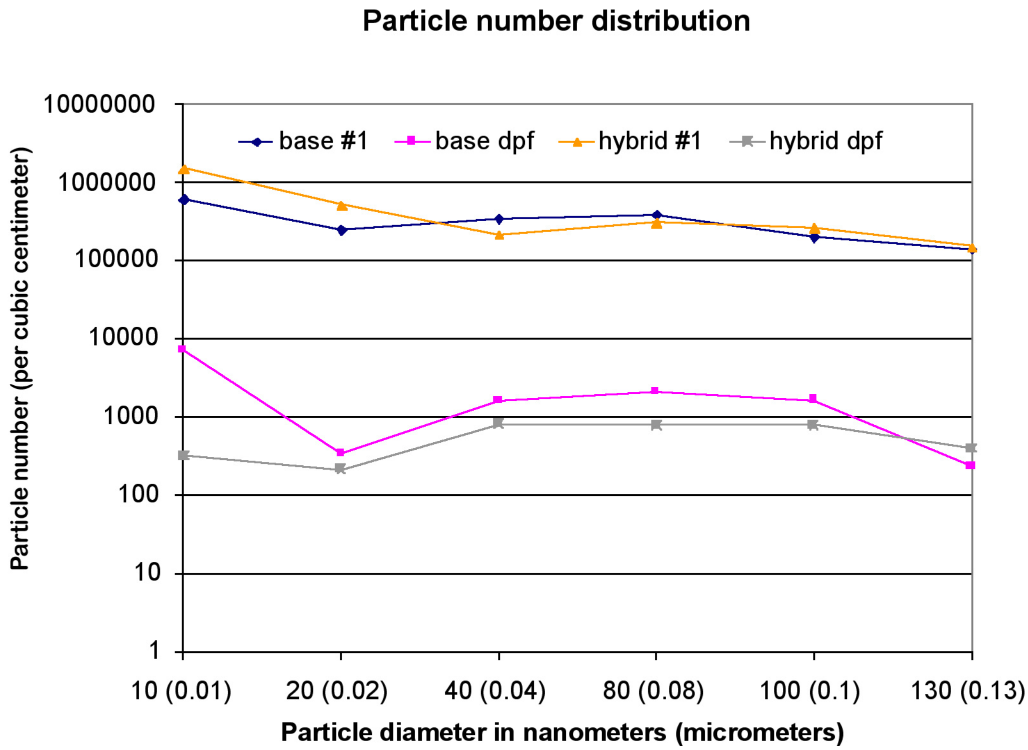


Figure 13: Particulate number distribution emitted from the hybrid buses and from the base clean-diesel buses on the Farmington Avenue route. The two cases shown are for bus operation using Number 1 diesel fuel and for operation with the bus fitted with a diesel particulate filter and using ultra-low-sulfur diesel fuel. The results for both bus types are nearly identical. In both cases, the particle numbers 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 micrometers). (Holmén, et al, 2005, on the CD)

In addition to the measurements described above, a widely used method of PM measurement, which is a measurement of the total mass of the PM (in grams per mile) from the exhaust, was also included in this study. The results are summarized in Figure 14.

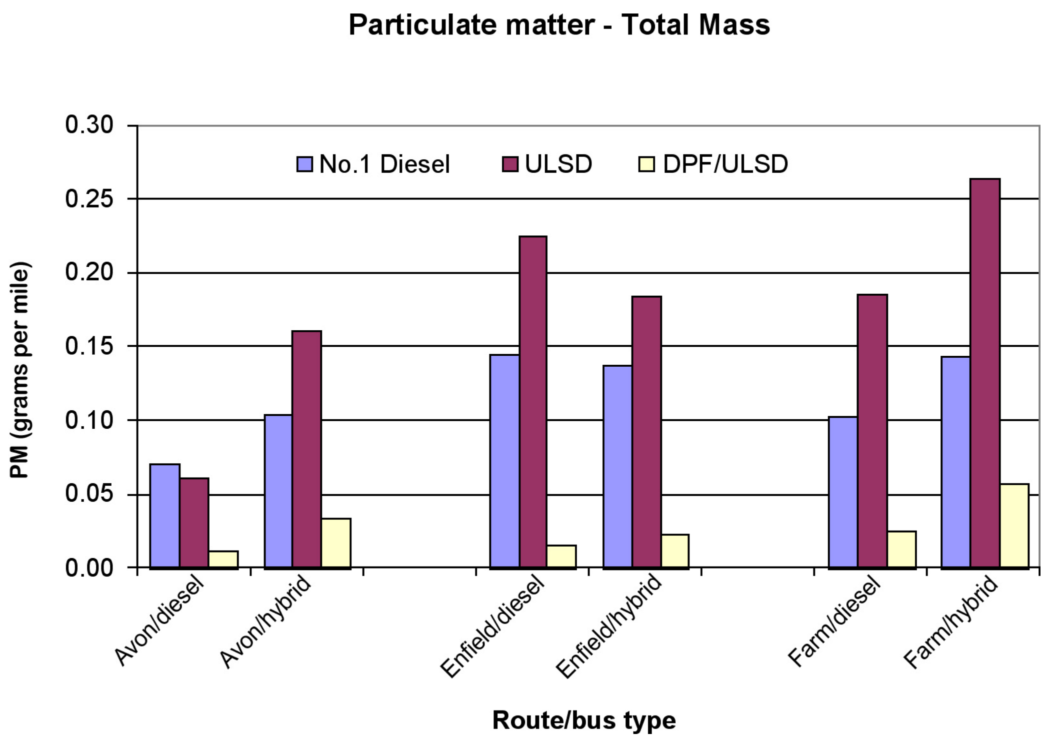


Figure 14: Chart illustrating the route average particulate mass emissions, in grams per mile, for the hybrid buses and for the base clean-diesel buses. The data are shown for the three routes studied (Avon, Enfield, and Farmington Avenue) and also for the three fuel/exhaust system situations (Number 1 diesel fuel, ultra-low-sulfur diesel fuel, and for buses fitted with diesel particulate filters and operated on ultra-low-sulfur diesel fuel (Holmén, et al, 2005, on the CD)

As may be seen, the PM total mass was more or less comparable for buses operated on Number 1 diesel fuel and on ultra-low-sulfur diesel fuel. However, it is somewhat surprising that the levels for the mass emission rate for the ULSD were usually somewhat higher than the levels for the Number 1 diesel case.

The Study Committee was somewhat concerned and puzzled by the results of changing from Number 1 fuel to ULSD. The only obvious change, from a physics and chemistry point of view, would be the elimination of sulfur compounds from the exhaust, which should have resulted in a slight lowering of the PM levels.

In response to the Study Committee's question, the principal investigator (Holmén) noted that the data for Number 1 fuel was taken in the winter, whereas the data for ULSD was taken in the summer. Because particle formation is sensitive to intake air relative humidity and temperature, this change in conditions could be responsible for the results. Also, it is well known in the emissions community that total mass measurements for modern diesel power buses are very difficult, with mass changes on the test samples on the order of a few micrograms.

In any case, with the addition of the DPF, the PM total mass was substantially reduced. In fact, the levels of mass indicated in the chart for the DPF case have high uncertainty because the mass collected was usually near the threshold limit of measurement. In contrast, the data for the particle number distribution shown in Figure 13 were adequately above the limits of measurement to enable reliable comparisons. This observation has significant implications for accurate particle measurement techniques of future fleet vehicles.

The great reductions in small diameter particulate matter with the use of a diesel particulate filter have been seen in several other independent studies. Some of the more prominent of these include Ayala (2005) [Trucks], Ayala (2002) [Buses], and Lanni (2002) [Buses].

IV. RELIABILITY, PERFORMANCE AND SURVEYS

RELIABILITY

During the course of this program, bus reliability was evaluated using two measures:

- Miles traveled between road calls, and
- Maintenance costs

The Study Committee was pleased by the results in all cases. The two hybrid buses and the two base clean-diesel buses have demonstrated levels of miles traveled between road calls that are considerably greater than the rest of the CTTransit fleet, and levels of maintenance costs per mile that are significantly less than the rest of the fleet. These results are shown in Figures 15 and 16. (Note that these measurements were taken by CTTransit personnel.)

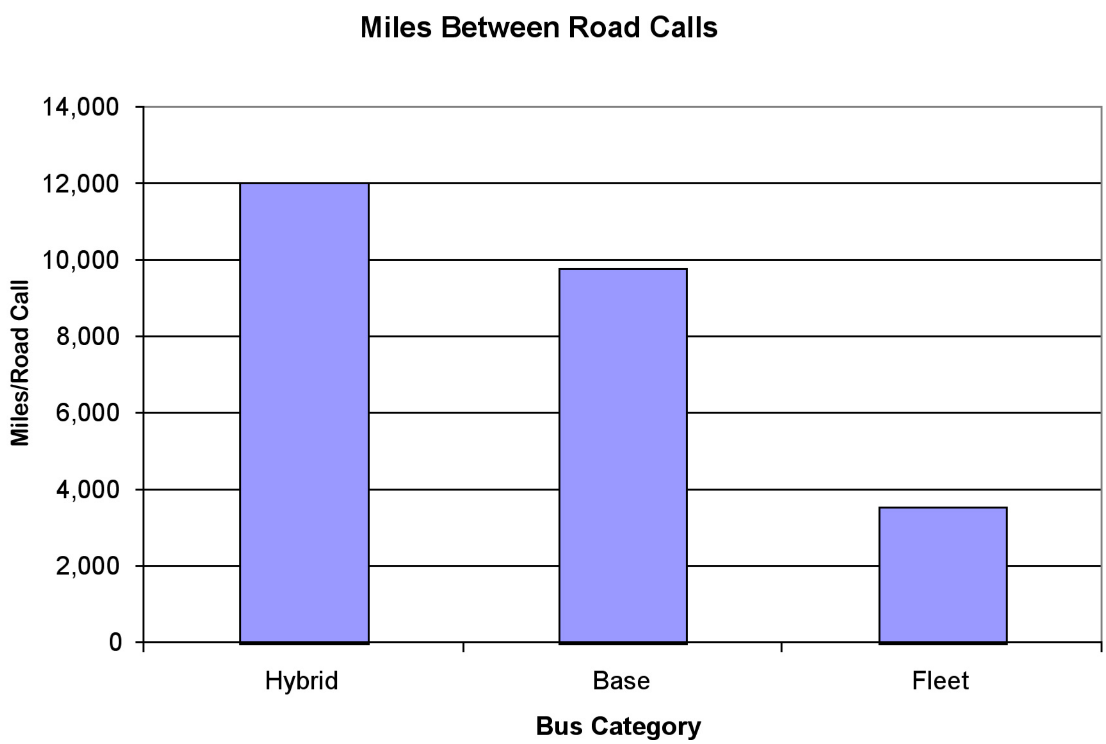


Figure 15: Average bus miles traveled between road calls for the hybrid buses, the base clean-diesel buses, and the rest of the CTTransit fleet. The miles/call are significantly greater for both the hybrid buses and the base buses, as compared to the rest of the fleet.

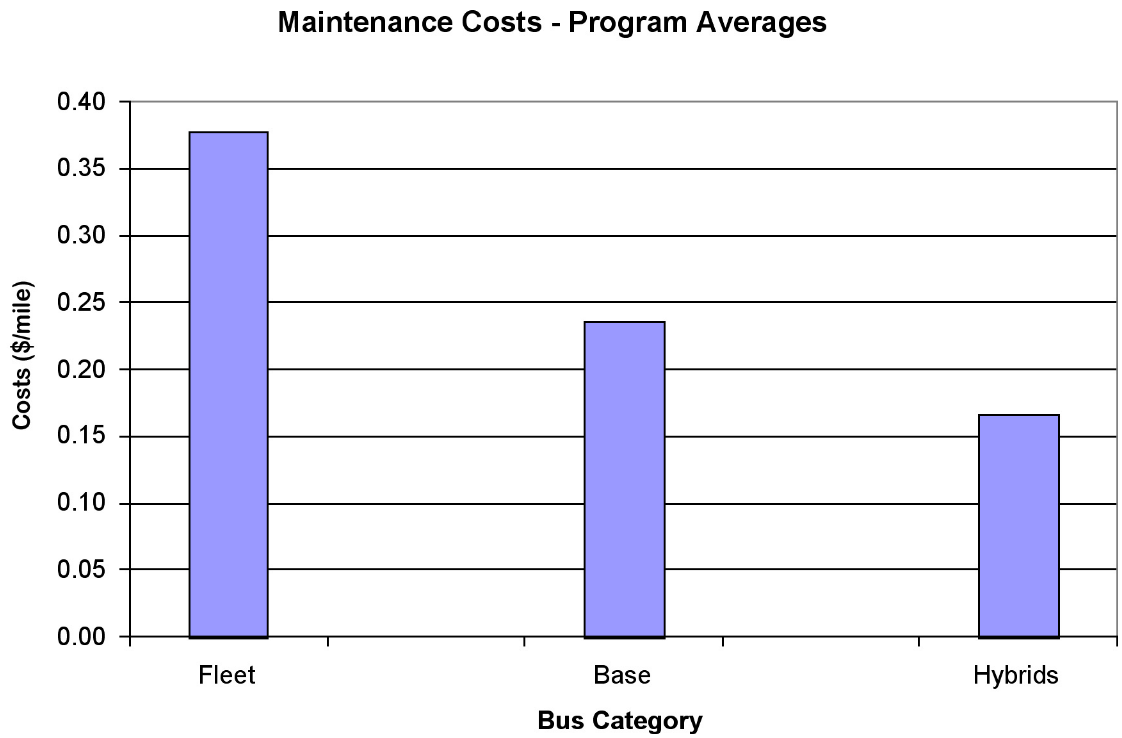


Figure 16: Program average maintenance costs, in $/mile for the hybrid buses, the base clean-diesel buses, and the rest of the CTTransit fleet. These costs are significantly less for both the hybrid buses and the base buses, as compared to the rest of the fleet.

Comments on Reliability, and Prospects for the Future

The initial data on reliability for both the hybrid buses and the base buses are very promising and encouraging. However, it is also the case that these buses are relatively new, compared to the rest of the fleet, and we would expect the initial results to be good. For the future, our expectations and questions include the following:

- For the base buses, the reliability performance will track, more or less, the performance of the rest of CTTransit's fleet, which is exclusively diesel powered. However, this performance may be better than the present fleet, since both bus and engine manufacturers continue to improve their products in response to both customer expectations and government regulations.

- For the hybrid buses, the initial reliability performance has met and exceeded expectations. There have been no apparent significant problems, despite the fact that these buses are of new design, and are early in the product cycle.

- Significantly fewer maintenance events for the engines, the transmissions, and the brakes are expected for the hybrid buses. These expectations are based on the inherent operation of the hybrid bus, compared to a conventional bus.

- It is too early to assess reliability for the batteries used in the hybrid bus propulsion system. However, it should be noted that this same battery technology (nickel-metal-hydride) is used in the Toyota's Prius hybrid automobile. It has been reported that the reliability results have exceeded expectations for the Prius.

BUS PERFORMANCE

There were initial concerns about some performance aspects of the hybrid buses. These concerns included:

- range
- availability
- top speed
- extended highway driving
- hill-climbing ability

In all cases, at least to date, these concerns are unfounded. The performance of the hybrid buses is comparable to that of conventional buses.

As a final note on bus performance, the acceleration of the hybrid buses, especially for a standing start, substantially exceeds that of conventional buses. The feature has been very well received by the bus drivers, as noted in the following section on Surveys.

SURVEYS

During the course of this program, about 100 passengers and about 28 drivers were surveyed. These surveys indicated that both the passengers and the drivers preferred the hybrid buses. Of passengers, 88% preferred the hybrid bus while 12% did not. For the drivers, 80% preferred the hybrid while 20% did not. Some of the features that were especially favored were:

- *by the passengers*, lower levels of noise and vibration
- *by the drivers*, better acceleration (93% liked this feature of the hybrid)

V. COST

The estimated life-cycle costs of ownership for the hybrid buses and for the base clean-diesel buses have been projected, based on known factors (purchase cost, current fuel economy and current maintenance costs) as well as estimates of longer term maintenance costs, including replacement of the hybrid bus battery pack. The following table shows estimates for

- the total cost, including the full value of the purchase cost
- the cost to Connecticut, assuming that the current purchase cost subsidy by the federal government (80%) remains in effect

(Please note that the data presented in this table were provided by CTTransit, and are based substantially on CTTransit's extensive history of transit bus operation and maintenance for Connecticut-based service).

	Total Costs			Costs to Connecticut	
Cost Item	**Conventional Bus**	**Hybrid Bus**		**Conventional Bus**	**Hybrid Bus**
Purchase Cost	320,000	500,000		64,000	100,000
Engine Rebuild	50,000	25,000		50,000	25,000
Transmission Rebuild	30,000	10,000		30,000	10,000
Battery Replacement	0	20,000		0	20,000
Fuel	171,429	156,522		171,429	156,522
Brake Maintenance	18,000	12,000		18,000	12,000
Diesel Particulate Filter Maintenance	12,000	6,000		12,000	6,000
Other Normal Miscellaneous Maintenance	150,000	150,000		150,000	150,000
Totals	**$751,429**	**$879,522**		**$495,492**	**$479,522**

Table 4: Estimated life-cycle cost of a conventional bus vs. a hybrid bus in dollars

COMMENTS ON COST ESTIMATES

Purchase Cost

The numbers listed in the table are approximate current costs. It is expected that the hybrid bus purchase cost will decrease as production volumes increase.

For the "Total Costs" columns, the full purchase prices are listed. For the "Cost to Connecticut" columns, the prices listed are based on the current federal subsidy of 80% for transit buses.

Engine Rebuild

The numbers listed are based on CTTransit's experience with conventional diesel buses and the expectations for the hybrid buses. For the conventional buses, the $50,000 is based on two engine rebuilds during the 12-year, 360,000-mile life of the bus. For the hybrids, the number shown is for one rebuild, which is the current expectation. This expectation of fewer rebuilds is based largely on the fact that the hybrid bus engine is stressed significantly less during operation. In particular, the engine does not provide significant power in the low speed and acceleration parts of the bus cycle.

Transmission Rebuild

The numbers shown are based on CTTransit's experience with conventional diesel buses and the expectations for hybrid buses. For the conventional buses, the $30,000 is based on three transmission rebuilds, whereas for the hybrid buses, the number reflects one rebuild. The hybrid bus expectation is based on two factors: first, the transmission is stressed considerably less during operation; and second, the current periodic examination of selected parts of the transmissions has revealed very low levels of wear. In particular, the wear plate of one of the transmission clutches was found to have its original identification number intact after over 50,000 miles of service. This low level of wear is unheard of in conventional transit buses.

Battery Replacement

The current expectation is that the battery pack will need replacement after six years of service. Only time will tell if this expectation is realistic. However, the reliability data for batteries of this type (nickel-metal-hydride) have been very good in hybrid automobiles.

Fuel

The numbers shown are for 360,000 miles of service, at 4.2 MPG for the conventional bus and 4.6 MPG for the hybrid bus, and a fuel price of $2 per gallon. The study committee understands that newer versions of the hybrid bus, which incorporate some changes in the control program and which also use a smaller engine, have shown still better fuel economy. However, it is important to note that the use of a smaller engine may limit the usefulness of the hybrid bus on some of CTTransit's routes (i.e., the Enfield express route and the Avon Mountain route, both of which may call for more sustained power than the smaller engine may be able to deliver).

Brake Maintenance

The numbers shown are based on twelve brake service events for the conventional bus, and eight events for the hybrid bus. These numbers are based on CTTransit's experience with conventional diesel buses and the expectations for the hybrid buses.

Diesel Particulate Filter Maintenance

The numbers shown are based on 24 maintenance events for the conventional bus and 12 events for the hybrid bus. The lower number of events for the hybrid bus is based on the relatively smaller variation of the DPF temperature that has been observed in the course of this program. This smaller variation is expected to result in lower levels of filter clogging, and improved life between maintenance events.

Other Normal Miscellaneous Maintenance

The numbers shown are estimates that are based on CTTransit's maintenance of its fleet. Although the maintenance costs on both the new conventional buses and on the hybrid buses are substantially less than those for the overall fleet, this analysis utilizes the more conservative figure.

Comment on purchase costs

As future regulations for emissions from transit buses are implemented, it is expected that the purchase costs for both the hybrid buses and for the conventional buses will increase. However, as hybrid bus technology matures, and as the volume of hybrid bus production increases, it is expected that the differential in purchase costs between hybrid buses and conventional buses will at least remain constant, and will perhaps decrease.

A hybrid bus, optimized for lower life-cycle cost

The study committee conducted a discussion as to some of the features of a future, lower life-cycle cost bus. Some of the thoughts that emerged include:

- a smaller diesel engine, allowing for more efficient engine operation
- a larger battery pack, and more substantial exercise of the battery pack

The smaller engine could reduce, slightly, the purchase cost of the bus, whereas this engine/battery pack combination could result in substantially better fuel economy. Also, this combination could result in still further improvements in brake lifetime, allowing a further reduction in costs.

VI. SUMMARY OF FINDINGS AND CONCLUDING REMARKS

SUMMARY OF FINDINGS

Fuel economy

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%.

Emissions

For any given fuel/exhaust gas treatment situation, the gaseous emissions (carbon dioxide, carbon monoxide, oxides of nitrogen, and unburned hydrocarbons) and particle mass and number emissions were virtually identical for the hybrid buses and the base clean-diesel buses when averaged over the real-world driving routes used in this study.

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

Reliability, performance, and customer surveys

Both the two hybrid buses and the two base clean-diesel buses have demonstrated levels of reliability (as measured by miles traveled between road calls, and maintenance costs per mile) that are significantly better than the rest of the CTTransit fleet.

The initial data on reliability for both the hybrid buses and the base buses are very promising and encouraging. However, it is also the case that these buses are relatively new, compared to the rest of the fleet, and we would expect the initial results to be good.

For the hybrid buses, their initial reliability performance has met and exceeded expectations. There have been no apparent significant problems, despite the fact that these buses are of new design, and are early in the product cycle.

The performance of the hybrid buses has been at least comparable to that of the base clean-diesel buses for such important items as range, availability, top speed, extended highway driving, and hill-climbing ability, and superior in acceleration, particularly for a standing start.

Riders and drivers alike prefer the hybrid buses, particularly the lower noise and vibration (riders) and the acceleration (drivers).

Cost

The estimated full cost of ownership for the hybrid bus is substantially greater than that of the base clean-diesel bus (~ $880K vs. $751K), whereas the full cost of ownership to Connecticut is somewhat lower for the hybrid bus (~$480K vs. $495K) due to the current federal subsidy for bus purchases.

Taken at face value, the numbers noted above would suggest that, as long as the federal bus subsidy program is in effect, it would be beneficial to Connecticut to purchase mostly hybrid buses. However, it is important to note the following:

- The subsidy program usually has a limit on the total dollars available for bus purchase. For a fixed level of funding, a smaller number of hybrid buses could be purchased; and
- The cost estimates for operation and maintenance of the hybrid buses are based substantially on expectations of lower maintenance costs. These estimates have yet to be validated over several years of bus operation.

CONCLUDING REMARKS

Based on this study, the committee suggests the following:

- Continue the operation and evaluation of the two hybrid buses, to help in guiding possible future purchases. In particular, continue to track the fuel economy and maintenance history of these buses.
- Consider a follow-up study of cost, reliability, and emissions, after several years of bus operation, to evaluate the aging of both the hybrid buses and the base buses.
- 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.
- However, at least for the present time, for the majority of the CTTransit fleet, continue to purchase conventional clean-diesel buses, fitted with state-of-the-art exhaust systems (including diesel particulate filters) and operate those buses on ultra-low-sulfur diesel fuel. (It is interesting to note that an essentially identical recommendation was made by Heywood, et al [Heywood, 2002] to the Massachusetts Bay Transportation Authority.) Also, these suggestions are consistent with those identified by CASE to CTTransit in earlier reports (CASE 2001 and CASE 2003).
- Share the results of this study with the larger US bus community, with the expectation that these results, shared with others and combined with other results, will help to shape the US transit bus community to both its and Connecticut's mutual advantage.

APPENDICES

EXECUTIVE SUMMARY
CTTRANSIT HYBRID AND CONVENTIONAL BUS GAS EMISSION MEASUREMENT TEST REPORT

Prepared by: Baki M. Cetegen, PhD; Professor, Department of Mechanical Engineering, University of Connecticut

Connecticut Transit, CTTRANSIT, the bus system owned by the Connecticut Department of Transportation, acquired two hybrid diesel-electric buses equipped with parallel Allison hybrid drives in the spring of 2003. An emission test program was planned to evaluate the emission performance of these 40 ft long New Flyer municipal buses and compare their performance with similar conventional diesel buses using #1 and low sulfur diesel fuels. Emission test program was originally planned to be conducted on a chassis dynamometer with laboratory emission test equipment. However, due to the limitations of the chassis dynamometer, particularly its inability to perform coast-down, the test program was restructured for on-road testing with mobile testing equipment. Testing involved measurements of gas emissions (CO2, NOx, CO, and hydrocarbons) along with different types of particulate testing involving both total particulate mass and size segregated measurements. The particulate tests were conducted concurrently with the gas emission tests and those results are presented in a separate report. This report deals with the gas emission tests for the two hybrid and two conventional diesel buses with tests performed on three different routes in the Hartford metropolitan area.

Test results indicate no discernible differences between the hybrid and conventional diesel buses in terms of the CO_2 and NO_x mass emissions for all test routes. Both types of buses exhibited higher CO and hydrocarbon emission on the city route with many stops as compared to the other two routes with higher speed and steep grades. When the NO_x emissions were normalized with the CO_2 emissions, 40 to 50 % reduction of this ratio for the hybrid buses with respect to the conventional buses was observed on the steep grade route. This was attributed to the engagement of the hybrid system, particularly on the uphill portion of the route. The repeatability tests indicated that CO_2 and NO_x emission measurements were repeatable within 10 %, while a higher degree of variability was observed for the CO and hydrocarbon emissions. Finally, state of charge corrections may have been necessary for some of the routes but the lack of sufficient number of tests for these corrections precluded the corrections from being implemented.

EXECUTIVE SUMMARY
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

On-board emissions testing of particulate matter from two transit buses powered solely by a diesel engine were compared to those of two parallel-design Allison E^P 40 hybrid diesel-electric buses under similar fuel and aftertreatment conditions. The two bus types had identical 40-foot low-floor New Flyer chassis and diesel engines of 280 hp power rating certified to the same emissions standards (the diesel engines were 2002 DDC series 40E and hybrids were 2003 Cummins ISL 280). Emissions were measured as the buses traveled on three bus routes in the Hartford, CT region – freeway commuter (65 mph cruise), a local business district (start-stop), and a suburban route with high grade – during three phases of testing from January to November 2004. Three combinations of diesel fuel and aftertreatment device were tested for both the diesel and hybrid bus types:

1. No. 1 diesel fuel + diesel oxidation catalyst (DOC) aftertreatment.
2. Ultralow sulfur diesel fuel (ULSD) + diesel oxidation catalyst (DOC).
3. ULSD + diesel particulate filter (DPF).

The measured No.1 diesel fuel sulfur concentration ranged from 230 to 320 ppm and the ULSD used in this study had 8 to 50 ppm sulfur. Particle number emissions were quantified using an SMPS and an ELPI. Total particulate mass emissions were quantified using a filter-based gravimetric technique. All particulate measurements were made after diluting vehicle exhaust with a single-stage ejector diluter system using dry, particle- and hydrocarbon-free air. *For each phase of testing (listed above), the route-average hybrid bus particulate mass and number emissions were not significantly different from the diesel buses at the 95% confidence level.*

Measured PM mass emissions ranged from 0.02 to 0.50 g/mi (mean = 0.16; sd = 0.09) for operation in Phases 1 and 2 (without the DPF) and were 0.004 to 0.10 g/mi (mean = 0.03; sd = 0.02) for operation with a DPF. The on-board measured mass emission rates are similar to literature values reported for laboratory dynamometer tests of transit buses and document the significant reduction in particulate emissions achievable with diesel particulate filters. In fact, *particle mass and number emissions were reduced to background levels when the buses were outfitted with DPFs*. The percent reduction in number (> 95%) and mass (>70%) emissions when operating with the DPF were similar for the diesel and hybrid buses. The lower percent reduction for <u>mass</u> measurement of DPF effectiveness (ranged from 69 to 97%) is due to the higher detection limits of the gravimetric technique compared to SMPS and ELPI number measurements.

Particle mass and number emissions for these relatively new (2002/2003 model year) diesel transit buses were not reduced significantly by lowering the diesel fuel sulfur content. This observation did not vary with driving route or bus type and was confirmed for data collected on PM filters, the SMPS and the ELPI. However, operation on ULSD enables the use of diesel particulate filter (DPF) aftertreatment. Therefore, the study results suggest that *CTTRANSIT should work to put DPFs into service on older engine buses in their fleet over the next 5-10 years to reduce overall fleet emissions until the current fleet is replaced by newer low-emission technologies*.

The study results demonstrate the feasibility of collecting on-road particulate mass- and number-weighted emissions data during operation on actual bus routes. The Allison parallel hybrid technology in its 'as-received' control configuration, did not result in any significant emission benefits over the diesel buses, but may have other fuel economy and maintenance benefits that are not addressed by this study. CTTRANSIT should investigate whether a series hybrid design will offer more emissions benefits without sacrificing other advantages of the parallel hybrid bus such as lower noise, smoother rides and performance characteristics comparable to conventional diesel transit buses on freeway commuter routes and routes with high grade (up to 9% in this study).

REFERENCES

Ayala (2005) – Alberto Ayala and Jorn Dinh Herner, "Transient Ultrafine Particle Emission Measurements with a New Fast Particle Aerosol Sizer for a Trap Equipped Diesel Truck," SAE paper 2005-01-3800

Ayala (2002) – Alberto Ayala, Norman Kado, Robert Okamoto, Paul Rieger, Britt Holmén, and Keith Stiglitz, "ARB's Study of Emissions from Two "Late-Model" Diesel and CNG Heavy-Duty Transit Buses," California Environmental Protection Agency, Air Resources Board, at the 12th CRC On-Road Vehicle Emissions Workshop, April 15-17, 2002, San Diego, CA

CASE (2001) – "A Study of Bus Propulsion Technologies Applicable in Connecticut." February 23, 2001

CASE (2003) – "Study Update: Bus Propulsion Technologies Applicable in Connecticut," March 2003

Consumers Report, May, 2005

Heywood (2002) – John B. Heywood, Jonathan Borak, Bill Parsley, Theodore Pickett, and Michael J. Widmer, "FY 2003 Two Hundred Bus Procurement," Expert Panel Report to Massachusetts Bay Transportation Authority, October 2, 2002.

Lanni (2003) – Thomas Lanni, Brian P. Frank, Shida Tang, Deborah Rosenblatt, and Dana Lowell, "Performance and Emissions Evaluation of Compressed Natural Gas and Clean Diesel Buses at New York City's Metropolitan Transit Authority," SAE paper 2003-01-0300

The New York Times, July 17, 2005, page 16

MAJOR STUDIES OF THE ACADEMY

2005

- An Evaluation of Asbestos Exposures in Occupied Spaces

2004

- Long Island Sound Symposium: A Study of Benthic Habitats
- A Study of Railcar Lavatories and Waste Management Systems

2003

- An Analysis of Energy Available from Agricultural Byproducts, Phase II: *Assessing the Energy Production Processes*
- Study Update: Bus Propulsion Technologies Available in Connecticut

2002

- A Study of Fuel Cell Systems
- Transportation Investment Evaluation Methods and Tools
- An Analysis of Energy Available from Agricultural Byproducts, Phase 1: *Defining the Latent Energy Available*

2001

- A Study of Bus Propulsion Technologies in Connecticut

2000

- Efficacy of the Connecticut Motor Vehicle Emissions Testing Program
- Indoor Air Quality in Connecticut Schools
- Study of Radiation Exposure from the Connecticut Yankee Nuclear Power Plant

1999

- Evaluation of MTBE as a Gasoline Additive
- Strategic Plan for CASE

1998

- Radon in Drinking Water

1997

- Agricultural Biotechnology
- Connecticut Critical Technologies

1996

- Evaluation of Critical Technology Centers
- Advanced Technology Center Evaluation
- Biotechnology in Connecticut

1994

- Science and Technology Policy: Lessons from Six Amer. States

1992

- A State Science and Technology Policy
- Electromagnetic Field Health Effects

1990

- Biotechnology (Research in Connecticut)
- Economic Impact of AIDS Health Care in Connecticut

1989

- Science and Engineering Doctoral Education in Connecticut

1988

- Indoor Pollution: Household Survey
- Vocational-Technical High School Curriculum Evaluation

1987

- Waste Conversion for State Construction
- High Technology Plan for Connecticut

1986

- Automobile Emissions Testing
- Health Standard (for EDBs)

CONNECTICUT ACADEMY OF SCIENCE AND ENGINEERING
179 Allyn Street, Suite 512, Hartford, CT 06103
Phone or Fax: 860-527-2161
e-mail: acad@ctcase.org
web: www.ctcase.org

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.

Vision

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.

Goals

- 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.

Connecticut Academy of Science and Engineering
179 Allyn Street, Suite 512, Hartford, CT 06103
Phone or Fax: 860-527-2161
e-mail: acad@ctcase.org
web: www.ctcase.org