A STUDY OF BUS PROPULSION TECHNOLOGIES APPLICABLE IN CONNECTICUT

FEBRUARY 23, 2001

A REPORT BY
THE CONNECTICUT ACADEMY OF SCIENCE AND ENGINEERING

FOR THE
CONNECTICUT DEPARTMENT OF TRANSPORTATION
AND
CTTRANSIT™

The Academy

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BUS PROPULSION TECHNOLOGIES APPLICABLE IN CONNECTICUT

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The content of this report lies within the province of the Academy's Technical Board on Transportation Systems, and has been reviewed by its Chair, Mr. Herbert S. Levinson, Transportation Consultant. Dr. Michael Werle, Executive Director of the Academy, has edited the report, which is released with the Academy Council's approval.

Michael J. Werle
Executive Director

EXECUTIVE SUMMARY

STATEMENT OF INQUIRY

The Connecticut Department of Transportation (CONN-DOT) and Connecticut Transit (CTTRANSIT™) plan to replace the existing 400-bus fleet serving Hartford, New Haven, and Stamford over the next decade. Both organizations wish to introduce new bus propulsion technologies that will meet both transportation and environmental needs.

The Connecticut Academy of Science and Engineering (the "Connecticut Academy") was asked to evaluate available and emerging bus propulsion technology, and to suggest bus purchase scenarios to assist CONN-DOT and CTTRANSIT™ with decisions involving the purchase of 200 new buses between 2003 and 2008.

SUMMARY OF FINDINGS

This study was based on an extensive literature review of salient bus technology, surveys of and visits to manufacturers, meetings with bus operators, and discussions with various representatives of groups such as the Northeast Advanced Vehicle Consortium (NAVC) and the Clean Cities Coalition. This information was then analyzed in terms of bus availability, range, reliability, cost, emissions, and compatibility with CTTRANSIT™'s operating environment.

Many bus propulsion systems were reviewed, including diesel, electric trolley, compressed natural gas, methanol, liquefied natural gas, liquefied petroleum gas, ethanol, diesel-electric hybrid, and fuel cells. An initial screening led to detailed analyses of the following technologies:

- ***The existing diesel system,*** to provide a benchmark for cost, reliability, and emission comparisons;
- ***The "clean diesel" system*** that uses ultra-low-sulfur fuel and Continuously Regenerating Technology (CRT™) exhaust filters;
- ***The hybrid diesel-electric system*** being tested in several cities, and ordered with both regular and ultra-low-sulfur diesel fuel in New York City;
- ***The compressed natural gas (CNG) system****; and*
- ***The fuel cell-based system****.*

The analysis applied here did not focus on the specifics of the emissions technology, as it is developing to meet EPA set standards. Because of the numerous and rapid changes taking place in the development and introduction of emissions-reducing technologies, it was judged that this study could not adequately address the science of emissions and "pick the winners". Rather, the committee has chosen to chart a course for minimizing the fiscal risk of choice.

Diesel-powered buses now comprise almost 80% of the U.S. bus fleet. These buses offer excellent reliability and availability, low purchase costs (about $280,000 for a 40-foot bus), and good fuel mileage. However, while substantially cleaner than a decade ago (about 80% less particulate matter and 20% less nitrogen oxide emissions), diesel-powered buses currently being manufactured emit more emissions than buses powered by other technologies. They will not meet the 2004 Federal Environmental Protection Agency (EPA) standards unless emissions are further reduced. Such reductions can be achieved through the use of ultra-low-sulfur fuel and Continuously Regenerating Technology (CRT™) exhaust filters. Although these modifications involve modest additional fuel costs (about 10 cents per gallon), they result in substantially reduced emissions.

Hybrid diesel-electric buses have recently become commercially available. These buses combine the best features of diesel and electric propulsion. They offer the advantages of very low emissions, especially when operated on ultra-low-sulfur fuel; excellent fuel efficiency, especially in frequent-stop urban service; and excellent acceleration from a stop. However, they have the disadvantages of being a relatively new technology with limited operating experience in revenue service, having high initial vehicle cost, and having limited service reliability, especially regarding batteries.

Compressed natural gas (CNG) is the most widely used alternative fuel. CNG buses offer the advantages of general availability of vehicles and fuel (fuel is domestically produced), more than a decade of operating experience, and very low particulate matter emissions. However, CNG has several disadvantages, including considerable infrastructure costs for handling fuel and upgrading safety systems, reported lower reliability and fuel efficiency, and variable nitrogen oxide emissions, depending on system adjustments.

Fuel cells are an emerging technology that will probably become available for revenue service within this decade. They offer the advantages of very low emissions and quiet operation. However, they have the disadvantages of very high purchase costs, very limited operating experience, and an absence of established commercial sources.

The costs and emissions for these technologies were estimated and compared with the costs and emissions for conventional diesel propulsion to quantify the anticipated increase or decrease in the costs and emissions for each propulsion system. These values, in turn, were applied to five bus purchase options from which aggregate cost increases (including infrastructure, vehicles, fuel, and maintenance) and emission reductions were computed for the six-year period from 2003 to 2008.

RECOMMENDATIONS

Based on these comparisons, the study committee compiled five bus purchase options (A through E). Options A and B denote the use of conventional and new state-of-the-art diesel, respectively, with the use of ultra-low-sulfur fuel; Option C includes a mix of diesel buses and diesel-electric hybrid buses, both using ultra-low-sulfur fuel; Option D involves the use of mostly diesel-electric hybrids; and Option E involves utilizing CNG buses.

Of the five options presented in the study, the committee recommends the following:

- ***First choice:*** ***Option C, a mix of state-of-the-art diesel buses and hybrid diesel-electric buses.***

  This option appears to represent the best balance between:
  - aggressively pursuing lower emission levels
  - striving for cost-effective mixes; and
  - maintaining a fleet of reliable, available buses.

  This fleet mix matches the mixed market needs of CONN-DOT and CTTRANSIT™. The diesel-electric hybrids can operate in local service, while the "clean diesels" using ultra-low-sulfur fuel can operate along express routes and hilly terrain. Articulated buses are available using the basic diesel propulsion. Moreover, the mixed fleet minimizes any risk relative to the diesel-electric hybrid technology. However, if the development of hybrid diesel-electric buses should progress more rapidly than our current evaluation suggests, then an even more aggressive position regarding hybrid buses might be pursued.

- ***Second choice:*** ***Option A and/or B, a mix of conventional and state-of-the-art diesel buses, with the possibility of moving more aggressively into ultra-low-sulfur fuel buses fitted with advanced exhaust treatment systems.***

  This option represents the best choice in the event that:
  - diesel buses are able to meet the future EPA standards for emissions; and
  - hybrid diesel-electric buses are not able to meet the current expectations regarding reliability, availability, and cost (for example, if the costs of diesel-electric hybrid buses do not fall below ~$350,000 by 2004).

- ***Third choice:*** ***Option E, CNG buses, with an introductory year of diesel buses.***

  This option represents the best choice in the event that:
  - diesel buses are not able to meet the future EPA standards for emissions, even using ultra-low-sulfur fuel; and
  - hybrid diesel-electric buses are not able to meet the current expectations regarding reliability, availability, and cost.

In addition, CONN-DOT and CTTRANSIT™ should consider the purchase and testing of fuel cell-powered buses, at times and in numbers that are yet to be determined. Fuel cell-powered buses have considerable potential for operation as very quiet buses with very low on-board emissions. Viewed in this context, fuel cell-powered buses are an extension of hybrid technology. However, major advances are required in areas of cost reduction, reliability, and range before these buses will be appropriate for wide-scale transit applications. These buses should be considered for purchase as this technology emerges.

Finally, the study committee recommends that CONN-DOT and CTTRANSIT™ continue to closely monitor bus propulsion technologies due to the very rapid pace of change anticipated in transit bus propulsion, with improvements expected for many of the technologies examined here.

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I. INTRODUCTION

The 400 buses that now serve Connecticut's cities will be replaced over the next decade. Connecticut Transit (CTTRANSIT™), in conjunction with the Connecticut Department of Transportation (CONN-DOT), plan to systematically replace this fleet. They are looking for environmentally sensitive, cost-effective bus propulsion technologies that will meet both transportation and environmental needs.

Both groups have expressed a desire to take an environmentally pro-active role in replacing the fleet. As they acquire new buses, they want to reflect the many concerns of environmental and community groups. They want to introduce the best existing and emerging bus technologies — both those commercially available and those in advanced prototype development. In each case, the buses must meet the U.S. Environmental Protection Agency (EPA) standards for the year of purchase. These EPA Standards, shown in Table 1, call for major reductions in particulate matter (PM), oxides of nitrogen (NOx), and hydrocarbons (HC).

TABLE 1. EPA URBAN BUS ENGINE STANDARDS
(GRAMS PER BRAKE HORSEPOWER-HOUR)

Model year	Hydrocarbons	Carbon monoxide	Oxides of nitrogen (NOx)	Particulate matter (PM)
1990	1.3	15.5	6.0	0.60
1992	1.3	15.5	5.0	0.25
1994	1.3	15.5	5.0	0.07
1996	1.3	15.5	5.0	0.05
1998	1.3	15.5	4.0	0.05
2004	0.4	15.5	0.4	0.05
2007	0.14	15.5	0.2	0.015
2010	0.14	15.5	0.2	0.015

SCOPE OF INQUIRY

This Connecticut Academy inquiry on bus technology reflects these transportation and environmental needs. The committee evaluated available and emerging bus technologies, and suggests bus purchase scenarios that could serve as a basis for CT- DOT's purchase of 200 new buses between 2003 and 2008. The purchases will reflect the wide range of operating conditions throughout the state, including urban routes with frequent stops and relatively low speeds, and express routes with fewer stops and relatively higher speeds. In this report the committee:

- reviews the state of the art in current and emerging bus propulsion technology in terms of availability, emissions, reliability, and cost;
- presents detailed analyses and comparisons for the more promising technologies;
- sets forth various bus purchase programs, including their benefits and impacts, for the period 2003 to 2008; and
- suggests bus purchase strategies.

APPROACH

This inquiry was conducted according to the following systematic series of steps:

1. Meetings with representatives of CTTRANSIT™ and CONN-DOT to refine the initial terms of reference and to get their perspectives.*

2. A review and study of appropriate documents on bus technology. These included *Transportation Cooperative Research Reports 38* and *59* (published by the Transportation Research Board), the *General Accounting Office Report on Alternative Fuels*, and reports by the Department of Energy and the Northeast Advanced Vehicle Consortium

3. Distribution of a questionnaire to major manufacturers of transit buses to obtain information on the status and availability of various bus propulsion technologies.

4. Field visits to Lockheed Martin Control Systems and to the Orion group, partners in building hybrid diesel-electric buses.*

5. A field visit to the New York City Transit Authority (NYCT), operator of a substantial fleet of buses, including many diesel buses, many compressed natural gas (CNG) buses, and the largest U.S. test fleet of hybrid diesel-electric buses.*

6. A discussion with several representatives of the Clean Cities Coalition, a group sponsored by the U.S. Department of Energy

7. A thorough analysis of the assembled information in terms of availability, reliability, costs and emissions, and ability to meet Connecticut's operating conditions.

8. An analysis of alternative bus purchase scenarios, and preparation of suggested purchase scenarios.

*NOTE: A listing of persons contacted during this study is given in Appendix A.

II. BUS TECHNOLOGY REVIEW

Bus technology research has advanced significantly in recent years, spurred by increasingly stringent emissions requirements. Modern diesel buses are far cleaner than their predecessors, and efforts are underway to further reduce emissions. Buses utilizing compressed natural gas and other alternative fuel technologies are being increasingly placed in service by many transit agencies; hybrid diesel-electric buses are being field tested; and work continues on fuel cell technology.

This chapter presents an overview of the various bus propulsion technologies, detailed analyses and comparisons of costs and emissions for the more promising technologies, and implications for the near future. The analysis applied here did not focus on the specifics of the emissions technology, as it is developing to meet EPA set standards. Because of the numerous and rapid changes taking place in the development and introduction of such emissions-reducing technologies, it was judged that this study could not adequately address the science of emissions and “pick the winners”. Rather, the committee has chosen to chart a course for minimizing the fiscal risk of choice.

OVERALL ASSESSMENT

Bus technology varies in terms of development status, extent of use, body types, and propulsion systems. Buses vary in performance, capital and operating costs, and environmental impacts. Various studies of these technologies have reported slight to significant differences in these parameters. In addition, since the technology is evolving rapidly, the dates of investigation of the individual studies affect the results and conclusions.

Status

The diesel bus has dominated the urban transit fleet in North America for more than half a century. However, within the last decade, the transit industry has increasingly tested and used alternate fuel technologies. As shown in Table 2, the number of diesel alternatives has increased substantially, from about 2% of all transit buses in 1992 to over 5% in 1997. In 1998, diesel alternatives comprised 7% of the total bus fleet, with compressed natural gas buses (CNG) accounting for more than half of the total diesel alternatives.

TABLE 2. NUMBER OF FULL-SIZED TRANSIT BUSES IN NORTH AMERICA BY TYPE OF FUEL 1992 THROUGH 1997

Type of Fuel	1992	1993	1994	1995	1996	1997
Diesel	50,181	49,118	48,119	47,644	46,389	47,034
CNG	116	249	476	575	857	1,469
Ethanol	5	29	33	22	347	338
Diesel (particulate filter)[1]	236	411	1,275	1,212	418	218
Methanol	57	392	402	402	63	54
LNG	10	52	9	50	50	50
Liquefied petroleum gas	59	59	2	2	4	4
Electric battery	0	0	0	0	1	3
Other[2]	332	334	463	418	521	378
Total diesel alternatives	815	1,526	2,659	2,681	2,161	2,515
TOTAL	**50,996**	**50,644**	**50,778**	**50,325**	**49,550**	**49,549**

Source: National transit database, The Volpe Center, FTA.
Note: The table covers transit operators in urbanized areas with populations of 50,000 or more. The number of buses includes those on order but not received.

Trends in U.S. bus purchases over the next several years, as reported by Friedman (Friedman, 2000) are given below in Table 3.

TABLE 3. ESTIMATED BUS SHIPMENTS IN THE US, BY PROPULSION TECHNOLOGY FOR THE PERIOD 2000-2005 (*FRIEDMAN, 2000*)

Propulsion technology	**Year of Purchase**					
	2000	2001	2002	2003	2004	2005
Diesel	2950	2950	2900	2800	2700	2500
CNG	800	800	600	500	400	350
LNG	100	50	50	25	25	25
Hybrid	150	175	250	350	600	900
Fuel Cell	10	10	15	50	100	200

1 A particulate filter is a diesel engine exhaust treatment device designed to trap or otherwise destroy particulate matter.

2 "Other" includes fuel types in the national transit database categorized as other, kerosene, dual fuel, and gasoline

These estimates indicate that conventional diesel will continue to be the dominant propulsion technology between 2000 and 2005. However, alternative fuel technologies will represent a larger share of new purchases, increasing from 26% in 2000 to 38% by 2005.

Separate and independent estimates of present and future bus technologies were obtained from several major U.S. bus manufacturers. The results of this survey are summarized in Tables 4 and 5. Of the several bus manufacturers contacted, five responded to the survey. For these five manufacturers, diesel-powered buses were the dominant technology in revenue service. CNG was the major alternative fuel technology, accounting for about 6% of the total number of buses.

TABLE 4. BUSES IN REVENUE SERVICE FOR SEVERAL MANUFACTURERS
(*CONNECTICUT ACADEMY SURVEY, 2000*)

Propulsion method	Gillig	North American	New Flyer	Nova	Orion	Totals	Pct
Diesel	1000	1500	7600	6600	1000	17700	90.3
Hybrid diesel-electric	0	0	2	0	10	12	0.1
CNG	2	100	950	83	10	1145	5.8
LNG/LPG	42	200	50	57	0	349	1.8
Methanol/ethanol	7	0	0	391	0	398	2.0
Fuel cell	0	0	0	0	0	0	0.0
Totals	1051	1800	8602	7131	1020	19604	

TABLE 5. ESTIMATED DATES OF AVAILABILITY/PROTOTYPE DEVELOPMENT FOR NEWER TECHNOLOGY BUSES
(*CONNECTICUT ACADEMY SURVEY, 2000*)

Propulsion method	Gillig	North American	New Flyer	Nova	Orion
Clean diesel using ultra low sulfur fuel	ca 2001			ca 2000	
Hybrid diesel-electric	ca 2005	ca 2000		ca 2000	Note A
Fuel cell	ca 2012		tbd		2004

Note A: Orion hybrid diesel-electric buses are already in revenue service

Table 5 indicates that two manufacturers have buses that use ultra-low-sulfur fuel in prototype development, while three anticipate hybrid diesel-electric buses by 2005. In addition, Orion is now building hybrid diesel-electric buses for revenue service. Fuel cells are under study by Gillig and Orion.

General Comparisons

The electric trolley bus and conventional diesel bus have been proven in revenue service; the diesel bus remains the dominant vehicle manufactured, and (unlike most alternative fuel technologies) is available in a wide range of sizes, up to large articulated buses. CNG buses are the dominant clean fuel technology bus and are being made by several bus manufacturers. Hybrid diesel-electric buses, now mainly in prototype development, will likely constitute an increasing share of buses in revenue service in future years.

Operating Ranges

The reported daily ranges for several bus propulsion technologies are set forth in Table 6.

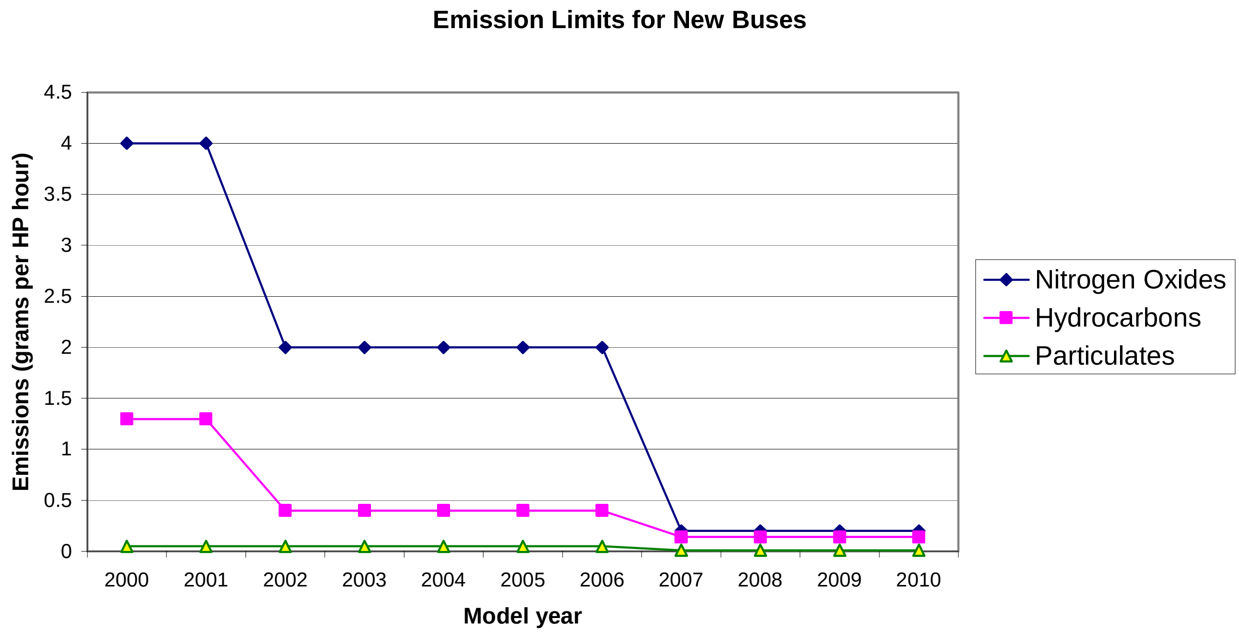
TABLE 6. REPORTED DAILY RANGES OF VARIOUS BUS TECHNOLOGIES (*FRIEDMAN, 2000*)

Fuel	Range (miles)
Diesel	400
Liquid Petroleum Gas	400
Liquid Natural Gas	350
Compressed Natural Gas	300
Alcohol fuels	<200
Diesel-electric hybrid	600
Fuel cell	<300

Emissions

The emissions from all new buses are expected to decline dramatically in the next several years, in response to U.S. government regulations. Figure 1 illustrates the actual or expected emission limits for new buses in the 2000-2010 time frame. For example, by the year 2007, the allowed limits for two key pollutants — oxides of nitrogen (NOx) and particulate matter (PM) — are expected to be reduced by a factor of more than ten compared to the year 2000. Also, the level of sulfur in diesel fuel will be reduced by at least a factor of ten, and perhaps by a factor of thirty, in this same time frame. These new emissions regulations are expected to have the greatest impact on new diesel buses. A key challenge for diesel engine manufacturers will be to meet these limits with engines that retain the reliability and cost features of present diesel engines.

FIGURE 1. ACTUAL OR EXPECTED EMISSION LIMITS FOR OXIDES OF NITROGEN (NO_X), PARTICULATE MATTER (PM), AND HYDROCARBONS FOR NEW MODEL YEARS 2000 TO 2010 (EPA WEBSITE, BUS AND TRUCK EMISSIONS)



Representative bus emission rates (in grams per mile), assembled from recent sources, are shown in Table 7 (p. 8). These rates include findings from the extensive analyses conducted by the Northeast Advanced Vehicle Consortium (*NAVC 2000*) for diesel, diesel-electric hybrids, electric, and CNG. This study provided a basis for many of the subsequent analyses set forth in this report. More detailed findings are given later in this report and also in Appendix B.

Bus emission rates vary by type and age of vehicle, method of propulsion and driving cycle. A review of Table 7 indicates the following:

1. New diesel buses have lower emissions than pre-1994 vehicles.

2. CNG and diesel-electric hybrids have lower emissions than diesel buses.

3. CNG buses have the lowest particulate emission rates. However, the NAVC study also found that diesel-electric hybrids had comparable emission rates to CNG when operated on ultra-low-sulfur fuel.

4. Hybrids had NOx emission rates that fall within the range reported for CNG buses.

5. Hybrids had lower Non-Methane Organic Compounds (NMOC), CO, and CO_2, rates than CNG.

6. Specific emission rates for other technologies were not available. The literature indicates that Liquified Natural Gas (LNG) performs similarly to CNG. Liquified Petroleum Gas (LPG) has lower emission rates than diesel, but higher than CNG.

7. Electric trolley buses and fuel cell powered buses have virtually no emissions, at least at the vehicle. (In a total system analysis, emissions created during power generation or fuel preparation should also be considered.)

TABLE 7. REPORTED EMISSIONS FOR VARIOUS BUS PROPULSION TECHNOLOGIES

	Emissions (grams per bus mile)					
Propulsion Technology	**Particulate matter (PM)**	**NOx**	**NMOC**	**CO**	**CO2**	**Source/Remarks**
Diesel	0.24	30.1	0.14	3.0	2779	NAVC 2000, Table A-1,Nova bus, CBD cycle
	0.7-1.6	20-60				Norton, Pre 1994 estimate
		23-28				Norton, 1994-present, estimate
Diesel-electric hybrid	0.22	19.0	0.08	0.1	2262	NAVC 2000, Table A-1 Orion bus, CBD cycle
Trolley	Nil	Nil	Nil	Nil	Nil	Estimated
CNG	0.02	9.7	0.6	10.8	2785	NAVC 2000 Table A-1Orion, CBD cycle
	0.02	25.0	2.36	0.6	2392	NAVC 2000, Table A-1 NeoPlan, CBD cycle
	0.0-0.1	5-85				Norton, Pre 1994
		18-41				Norton, 1994-present
LNG	Identical to CNG					GAO, 1999
LPG	Low	Low				GAO, 1999
	Minimal reduction over diesel					Friedman, 2000:
Methanol	None	Low				GAO, 1999
Ethanol	Low	Not well documented				GAO, 1999:
Fuel cells	None	Trace		Minimal		GAO, 1999

Costs

Generalized cost comparisons for the principal bus propulsion technologies are summarized in Table 8 (p. 9). Further narrative discussion of these technologies is outlined in Tables 9 and 10 (pp. 10 & 11). The data represent 1995-96 conditions, largely as set forth in *TCRP Report 38*, and hence need modification in terms of changes in fuel costs, capital costs, and the emergence of new technologies, such as the diesel-electric hybrid bus. Still, they provide insight into the comparative costs of various technologies. Comparisons are set forth for diesel, CNG, LNG, LPG, methanol, ethanol and fuel cells. The electric trolley bus, drawing power from overhead wires, was added in an effort to provide a comprehensive comparison.

TABLE 8. REPORTED COSTS FOR SEVERAL BUS PROPULSION POWER TYPES, AS OF 1996

Assumes 200-bus facility

FUEL TYPE	APPROX. NO. OF BUSES IN NO. AMERICAN TRANSIT FLEET (1997)	CAPITAL COSTS FUELING FACILITIES & OVERHEAD	CAPITAL COST MAINTENANCE GARAGE MODIFICATIONS	VEHICLE REPLACEMENT COSTS	FUEL COST PER BUS MILE	MAINTENANCE COSTS (RELATIVE TO DIESEL)	FUELING FACILITY O&M (RELATIVE TO DIESEL)	MAINTENANCE GARAGE O&M
Trolley Bus	1,060	Extensive	--	$600,000	Not Available	Lower	None	Lower
Diesel Bus	47,100	--	--	$250,000	0.22	Base	Low	Base
Compressed Natural Gas	1,470	$ 1,700,000	$600,000	$320,000	0.19	Higher	Very High	Higher
Methanol	50	$440,000	$340,000	$280,000	0.38	Highest	Low	--
Liquefied Natural Gas	50	$1,800,000	$600,000	$320,000	0.26	Higher	High	Higher
Liquid Petroleum Gas Propane	**5**	$700,000	$340,000	$290,000	0.34	Higher	Low	Higher
Ethanol	340	$440,000	$340,000	$280,000	0.52	Highest	Low	Higher
Hydrogen	0	>$1,7M	Not Available	$500,000	Not Available	Lowest	May be Highest	May be Highest

Sources: *TCRP Report 38*
Bus Fleet - General Accounting Office
Metro Magazine Sept., Oct. 2000
Trolley bus costs from *Transportation Planning Handbook, Second Edition*, Institute of Transportation Engineers, 1999

This table reflects costs as of 1995-1996.

TABLE 9. NARRATIVE DESCRIBING THE CAPITAL COSTS OF BUSES POWERED BY VARIOUS PROPULSION TECHNOLOGIES (*TCRP 38*)

FUEL	Capital Cost Element		
	Vehicle Replacement	Fueling Facilities	Maintenance Garage Modifications
Diesel	Lowest of any of the alternatives. $250,000 ea., low floor or lift equipped, w/air conditioning, HHD engine, electronic farebox & destination sign.	Costs are moderate and generally predictable. However, failing to contain leaks from underground storage tanks can lead to high remediation costs.	None. Existing garages are designed for diesel buses.
CNG	Most expensive except for hydrogen fuel cell. $320,000 each, w/400 mi. range. Equipped as with diesel, except that fire suppression system is normally specified.	Approximately $1.7M for 200 bus facility. Design for high mechanical loads, high pressure, plus need for drying & filtration makes cost high.	Methane detection, increased ventilation, classified (explosion proof) electrical service in selected locations, and fire protection control system upgrades. $600,000 median cost.
LNG	Somewhat less expensive than CNG, due to lower fuel tank cost. $305,000 each, with fire suppression system and methane leak detection system.	Approximately $1.8M for 200 bus facility — similar to CNG. Materials and designs for storing, pumping, and metering cryogenic fuels are costly. Mechanical and pressure loads are much lower than with CNG.	Same as CNG.
LPG	$290,000 each. Vehicle cost is similar to, or somewhat less than LNG. LPG tanks are not insulated, making them less expensive than LNG tanks. LPG buses should be equipped with fire suppression systems.	Approximately $700k. Design standards are quite mature; costs are predictable. Tanks must be strong enough to support moderate (250 psi) pressures. Fuel is non-toxic liquid at room temperature; material requirements are moderate.	None if garage is designed for gasoline vehicles. If not, increased ventilation, classified electrical service in low areas, and fire protection control system upgrades will be needed. Modifications should be less costly than for CNG or LNG, since LPG fuel leaks remain near the floor. $340,000 median cost.
Methanol	Somewhat higher than diesel ($280,000), due to larger fuel tank, higher engine cost and need for corrosion resistant materials in the fuel system. Fire suppression system is normally specified.	Somewhat higher than with diesel: Approximately $440k. Wetted materials must be selected carefully to resist corrosiveness of the fuel; vapor recovery system must be added. 2x storage tank volume needed vs. diesel.	Similar to LPG.
Ethanol	Similar to methanol.	Similar to methanol.	Similar to LPG.
Hydrogen	Most expensive, likely to be $500,000 ea. Would be used only in a fuel cell bus w/CH_2 storage. Fire suppression system would be specified.	Designs are in conceptual stage. L- CH_2 is a possibility, as is curb-side reforming from methanol. Likely to be more expensive than with CNG.	Need to mitigate very volatile, potentially explosive fuel leaks. Design standards and costs are not yet established.

TABLE 10. NARRATIVE DEALING WITH THE OPERATING COSTS OF BUSES POWERED BY VARIOUS PROPULSION TECHNOLOGIES (*TCRP 38*)

FUEL	Operating Cost Element			
	Vehicle Operating	Vehicle Maintenance	Fueling Facility O&M	Maintenance Garage O&M
Diesel	Fueling cost = ($0.87/gal)/(4 mi/gal) = $0.22/mi.	Lowest except possibly for hydrogen fuel cell. New electronically-controlled four stroke diesel engines are significantly more durable and maintainable than earlier two-stroke engines.	Low operating and maintenance costs. These include electric energy to pump fuel, annual tank pressure testing and operating permit renewal; and occasional servicing of dispensers and pumps.	Moderate HVAC energy costs: Ventilating rates must be high enough in repair bays to adequately dilute vehicle exhaust
CNG	Fueling cost = ($0.326/thm gas + 0.08/thm compression)/(2.14 mi/thm) = $0.19/mi. Bus is 35% less energy efficient than diesel bus.	Agencies report similar or moderately higher maintenance costs than with diesel buses. Greater engine complexity, design immaturity, and vehicle weight suggest that moderately higher maintenance costs will continue.	Highest, except possibly for hydrogen. High mechanical loads, vibration and fatigue wear potential exist with gas compressors. Gas dryers and filters need to be periodically serviced. Compression energy cost is significant.	Slightly higher maintenance costs exist vs. diesel for periodically testing and calibrating methane leak detectors.
LNG	Fueling cost = ($0.48/gal)/(1.83 mi/gal) = $0.26/mi. Bus is 30% less energy efficient than diesel bus.	Similar to CNG, except that rigorous inspection and maintenance programs in place for on-board CNG tanks at some agencies, could be avoided: LNG uses rugged moderate pressure tanks.	Lower than hydrogen or CNG, but higher than the other fuels. Mechanical and pressure loads are much lower than with CNG. Components are subject to severe thermal cycling. Pumps, valve packings and gaskets may have to be serviced or replaced frequently.	Same as CNG.
LPG	Fueling cost = ($0.65/gal)/(1.92 mi/gal) = $0.34/mi. Bus is 35% less energy efficient than diesel bus.	Similar to CNG.	Similar to diesel.	Similar to CNG, since fire protection system may also incorporate combustible gas detectors.
Methanol	Fueling cost = ($0.59/gal)/(1.54 mi/gal) = $0.35/mi. Bus is 15% less energy efficient than diesel bus.	Transit agencies have experienced very high maintenance costs due to frequent premature engine failures involving injectors, liners and bearings. Operating life between rebuilds is often 1/2 to 1/3 of diesel baseline.	With properly designed facility, operating and maintenance costs should be similar to diesel facilities. Improper material selection can lead to elevated costs for replacing hoses, product filter and gaskets and seals.	Similar to LPG.
Ethanol	Fueling cost = ($1.08/gal)/(2.06 mi/gal) = $0.52/mi. Bus is 15% less energy efficient than diesel bus.	Similar to methanol.	Similar to methanol.	Similar to LPG.
Hydrogen	Not yet established; several fuel supply scenarios are possible.	Could yield lowest powertrain maintenance cost of any propulsion mode, due to extreme mechanical simplicity of the PEM fuel cell propulsion system.	Fuel-island reformer designs are in conceptual stage, so no actual data exist. High system complexity and CNG-equivalent storage pressure suggest that operating an maintenance costs will be higher than with CNG.	No data exist, but likely to be higher than for CNG.

The electric trolley bus — established long before the diesel bus — has low operating costs, but very high installation costs. It is a clean fuel technology that eliminates emissions from buses, but it requires extensive infrastructure, making it suitable only for bus lines with high ridership densities, especially where power costs are low. Neither of these conditions is found in Connecticut.

The diesel bus has the lowest overall capital and operating costs of the various technologies, since it requires neither overhead power lines nor new fueling systems. However, its current emissions are higher than other technologies. Thus, improvements in fuel and in engines are essential if it is to become a clean fuel technology by 2004.

The various clean fuel technologies produce lower emissions than the diesel bus, and appear consistent with EPA emission standards for 2004, but they have higher overall costs. These include additional costs associated with fueling facilities and garage modifications, higher purchase costs for new buses compared to diesel, and generally higher fuel costs. In addition, there are some safety implications in dealing with these fuels.

As of 1995-96, fuel costs for diesel and CNG buses were comparable, while other propulsion technologies had higher fuel costs. However, overall fuel costs are sensitive to price changes of specific fuels over time.

Table 11 illustrates comparative fuel costs per bus-mile as reported in *TCRP Report 38* (1998) and in a TRB presentation by Friedman (Friedman 2000).

TABLE 11. COMPARATIVE FUEL COSTS PER BUS-MILE REPORTED IN *TCRP REPORT 38* (1998) AND IN A TRB PRESENTATION BY FRIEDMAN (*FRIEDMAN 2000*) (COSTS IN DOLLARS PER BUS MILE):

Fuel	**Year**	
	1998	**2000**
Diesel	$0.22	$0.21
CNG	0.19	0.21
LNG	0.26	0.50
LPG	0.34	0.50
Alcohol	0.38-0.52	0.50

Since January 2000, costs for both diesel and CNG have increased substantially. Diesel fuel purchased by CTTRANSIT™ is currently estimated at $1 per gallon (CTTRANSIT™, private communication), while the CNG spot price has more than doubled since the beginning of 2000, to $6 per million BTU.

Illustrative examples of annualized bus costs (dollars per year) for 10-, 50-, and 200-bus fleets are given in Figures 2A, 2B, and 2C. These cost comparisons are set forth in *TCRP Report 38* for several bus fleet sizes. It is clear from the charts that costs for CNG, LNG, and LPG are consistently 20 to 25% higher than those for conventional diesel buses. Costs for methanol and ethanol are even higher.

FIGURE 2A: ANNUALIZED COSTS FOR A 10-BUS FLEET, FOR BUSES POWERED BY DIESEL, CNG, LNG, METHANOL, ETHANOL, AND LPG (*TCRP 38*)

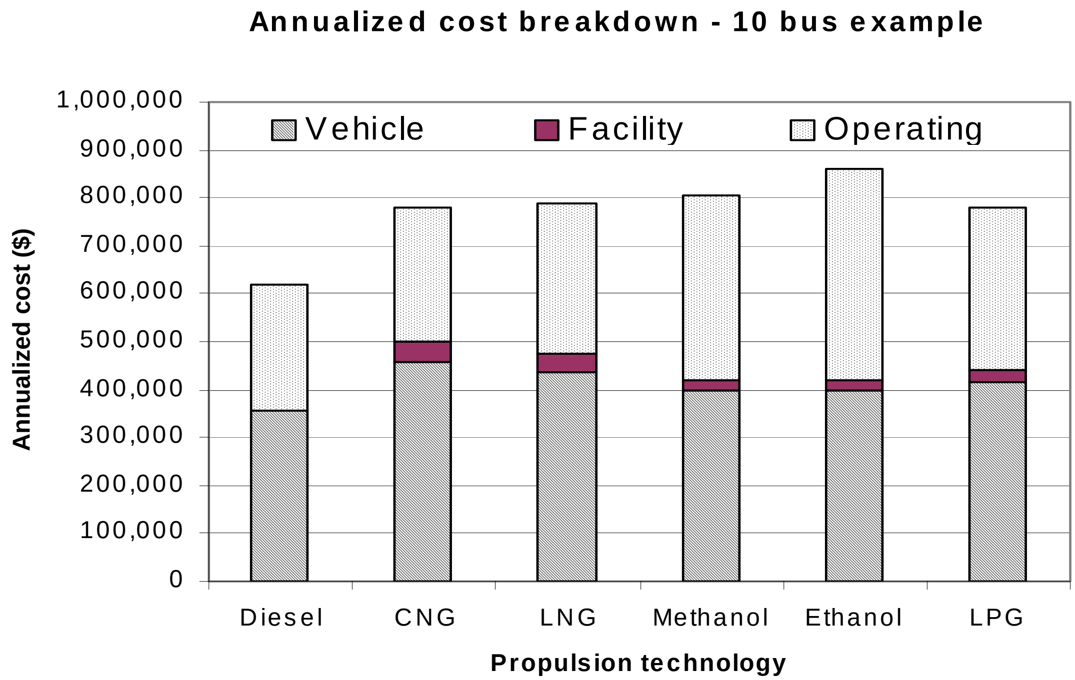


FIGURE 2B: ANNUALIZED COSTS FOR A 50-BUS FLEET, FOR BUSES POWERED BY DIESEL, CNG, LNG, METHANOL, ETHANOL, AND LPG (*TCRP 38*)

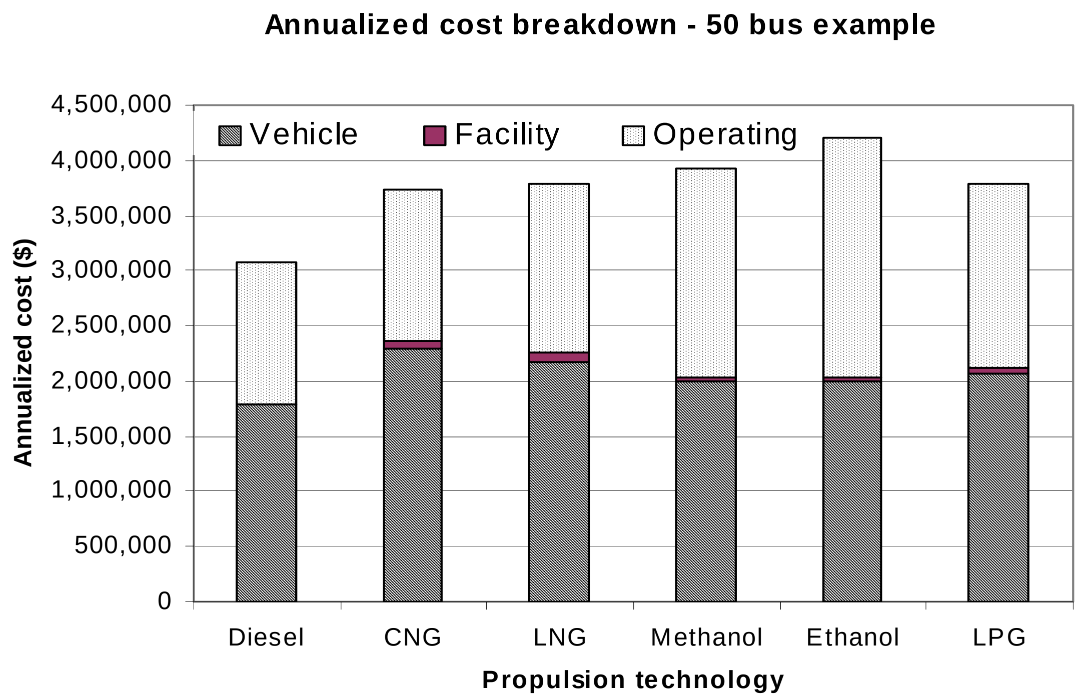
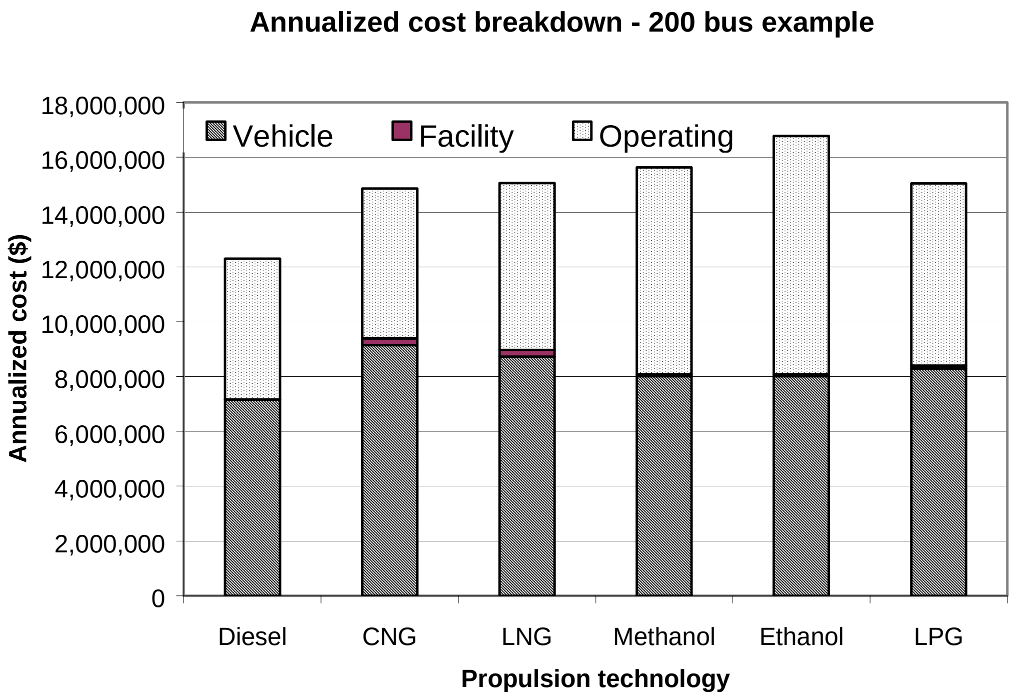


FIGURE 2C: ANNUALIZED COSTS FOR A 200-BUS FLEET, FOR BUSES POWERED BY DIESEL, CNG, LNG, METHANOL, ETHANOL, AND LPG (*TCRP 38*)



Implications

Diesel will remain the standard fuel for urban transit buses for at least the next decade. Diesel-powered buses afford superior fuel efficiency, have lower installation and operating costs, and have proven reliability. Emissions from these buses have been dramatically reduced over the past decade, but will need improvement to meet the 2004 emission standards. Accordingly, using the standard diesel as a benchmark, the study committee conducted a detailed analysis focusing on the following three basic technologies that have promise over the next ten years:

- "Clean diesel" buses modified to reduce emissions by using low-sulfur fuel and special particulate exhaust filters e.g., CRT™ systems.
- Diesel-electric hybrid buses such as those being field tested in New York City and several other cities. (New York City has ordered 125 diesel-electric hybrid buses.)
- CNG buses — the most widely used of today's alternative fuel technologies.

DETAILED ANALYSIS OF VIABLE BUS TECHNOLOGIES

This section contains a detailed description and analysis of the bus propulsion technologies that appear viable for CTTRANSIT™ over the next ten years. These technologies are: (1) diesel, including the use of ultra-low-sulfur fuel (< 50 ppm sulfur) and particulate exhaust filters; (2) compressed natural gas (CNG); and (3) hybrid diesel-electric using both regular and ultra-low-sulfur fuel. For each technology, the principle of operation, status of technology, emissions, reliability, and costs are presented and discussed. Some comments on the use of fuel cells as a propulsion technology are also included.

Diesel

As noted earlier, diesel-powered buses are expected to remain the dominant element of the transit bus fleet. These buses offer the advantages of:

- excellent reliability and availability
- low cost
- very good fuel economy
- widespread availability of diesel fuel
- general availability of engines from several manufacturers
- extensive in-service use by several transit systems

However, diesel engines have traditionally emitted greater amounts of several pollutants, including oxides of nitrogen (NOx), particulate matter (PM), and carbon monoxide (CO) than many of the other propulsion technologies. In fact, this feature of diesel buses has been largely responsible for the interest in alternative fuel buses.

Status

Diesel buses have been proven in revenue service throughout the world. Ultra-low-sulfur fuel is available in the northeast United States, at a small additional cost per gallon. Catalytic exhaust filters have been developed, but may need additional improvement.

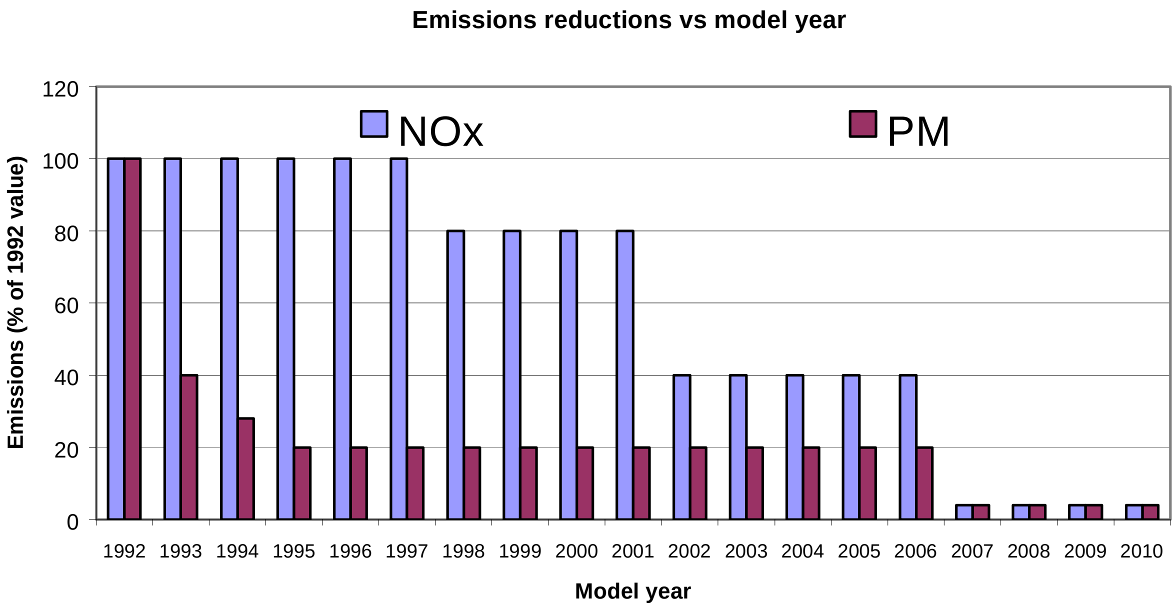
Principle of Operation

Diesel engines are compression ignition (CI) engines, with the heat of compression of the intake air used to generate the temperatures needed for ignition and combustion. All current diesel engines are of the four-stroke variety, with the usual intake, compression, ignition / combustion / power, and exhaust strokes. Due largely to the higher compression ratio (>20 to 1) that can be used with CI engines as compared to that of spark ignition (SI) engines (~10 to 1), CI engines can have considerably higher peak efficiencies (~40%) than similar SI engines. All currently manufactured CI engines operate on conventional diesel fuel, and we refer to these engines as “diesel” engines.

Emissions

Diesel emissions have been reduced in the past and are expected to be further reduced in the future. Figure 3 (p. 16) shows that buses purchased since 1998 emit 20% less NOx and 80% less PM than buses purchased in 1992.

FIGURE 3. U.S. GOVERNMENT LIMITS ON NOX AND PM EMISSIONS FROM



TRANSIT BUSES (EPA WEB SITE)

The present situation, and comments on the past: According to NYCT (Lowell, 2000A), diesel engines today are 94% cleaner than engines purchased ten years ago. Also, results of chassis dynamometer tests of the Combined Business District (CBD) duty cycle reported in *TCRP 38* also show substantial declines in NOx and PM emissions. For example, the NOx emission rate in grams per mile declined from about 45 in 1988 to 23 in 1993 — a 44% reduction — with PM emission rates reduced even further (*TCRP* 38, pp 71-72, figures 13-14.)

Despite these improvements, it is believed that further reductions in diesel emissions will be required to meet the post-2003 and still further improvements will be required to meet the post-2007 standards as given in Table 1 on page 1.

The future, ultra-low-sulfur fuel and exhaust filters: Compliance with the 2004 and 2007 emission rules will require, almost certainly, the use of ultra-low-sulfur fuel, complemented by particulate exhaust filters. The reduced sulfur fuel — at a level of 30 ppm sulfur and an additional cost of ~ $0.10 per gallon — is available in the northeast United States (Lowell, private communication). The Continuously Regenerating Technology exhaust filters (CRT™) include an oxidation catalyst and wall-flow ceramic filter, and are packaged to replicate OEM muffler dimensions. Although these filters are not currently in widespread use, there are no external moving parts and no external energy requirements that would suggest reliability issues.

The New York City tests of ultra-low-sulfur fuel and CRT™ particulate filters: NYCT is conducting a CRT™ exhaust filter fleet demonstration (*Lowell, 2000B*). The demonstration includes 50 buses equipped with CRT™ filters operating in revenue service in Manhattan for one year, including 25 1999 buses with Detroit Diesel Series 50 engines and 25 1993 buses with Detroit Diesel 6v 92 DDEC engines. One entire depot will operate with reduced-sulfur fuel.

Demonstration results of the 25 Series 50 buses operating since February 1, 2000 indicate that the in-service exhaust temperatures are acceptable. The CRT™-equipped buses have logged over 260,000 miles, with no CRT™-related road failures to date. The mean distance between failures is equivalent to that for non-CRT™ buses. There have been no back-pressure problems to date and no measured loss of fuel economy.

The emissions test results are shown in Table 12. The PM, HC, and CO emissions were comparable to those with CNG. Two points are significant: 1) In all cases, there are substantial reductions in CO, HC, and PM emissions, and small changes in NOx emissions; and 2) The *combination* of CRT™ and reduced sulfur fuel provides by far the greatest emissions reduction.

TABLE 12. SUMMARY OF RESULTS OBTAINED BY USING LOW SULFUR FUEL AND CRT™ PARTICULATE FILTERS ON A FLEET OF BUSES.
DETERMINED FOR THE CBD BUS CYCLE (*LOWELL, 2000B*)

DIESEL BUSES WITH:	**REDUCTION FROM BASELINE**			
	CO	**HC**	**NO_X**	**PM**
REDUCED SULFUR FUEL	23% to 33%	66% to 84%	8% incr to 9% red	13% to 33%
CRT™ & REDUCED SULFUR FUEL	89% to 95%	83% to 99%	0% to 9%	81% to 93%

Note:

- Baseline numbers consistent with other recent testing
- PM, HC, & CO emissions comparable to CNG
- Toxic analysis & particle size analysis not yet complete

Reliability

Diesel engine-powered buses are the accepted standard for reliability in transit buses. This is due to several factors, including:

- inherent simplicity of the diesel cycle
- extensive in-service experience for these buses
- availability of engines from several manufacturers

The reliability of diesel-powered buses is discussed in more detail in the following sections on CNG buses and on hybrid diesel-electric buses.

Costs

Diesel engine-powered buses are also the accepted standard for low cost in transit buses. This is due in large part to the same factors that establish these buses as standards for reliability. These costs (about $280,000 for a 40-foot bus) are discussed in more detail in the following sections on CNG buses and on hybrid diesel-electric buses.

Assessment

The diesel bus, using ultra-low-sulfur fuel and catalytic exhaust filters, offers the advantage of proven technology, reduced emissions, and low infrastructure and vehicle costs. These benefits depend on the ready availability of ultra-low-sulfur fuel.

Compressed Natural Gas (CNG)

CNG engines have been the overwhelming choice for buses operating on fuel other than diesel (see Figure 4). CNG buses offer the following advantages:

- very low levels of PM emissions
- naturally very low levels of sulfur in the fuel
- general availability of engines from several manufacturers
- extensive in-service use with several transit systems
- widespread availability of CNG fuel

However, these systems have the following disadvantages:

- infrastructure costs for handling the fuel, including upgrading safety systems
- availability / reliability issues -- 50-75% as reliable as comparable diesel buses in New York City (Lowell, 2000C)
- somewhat lower fuel efficiency, compared to CI / diesel systems, e.g., ~ 41% less energy efficient in some NYCT urban service, (Lowell 2000C)
- variable NOx emissions, apparently depending on system adjustments (NAVC, 2000)

FIGURE 4. PHOTOGRAPH OF A CNG-POWERED BUS

Status

CNG buses were placed in revenue service in the early 1990s. There has now been more than a decade of operating experience.

Principle of Operation

In contrast to diesel engines, which use the Compression Ignition (CI) engine cycle, CNG engines use the spark ignition (SI) engine cycle. In the SI cycle, a conventional spark plug generates the heat needed to ignite the fuel / air mixture in the engine cylinders. All current CNG engines are of the four-stroke variety, with the usual intake, compression, ignition / combustion / power, and exhaust strokes. Most of the currently available CNG engines are adapted from commercially available CI engines, with the addition of a spark plug in the engine cylinder and with modifications / additions to the engine control system. The SI cycle must be used when the chemical characteristics of the fuel (low Cetane number) make it unsuitable for CI operation. All SI engines operate with a lower compression ratio (~10 to 1) than CI engines (~20 to 1), with a correspondingly lower efficiency.

Emissions

The following comments refer to the results of the North American Vehicle Consortium report *(NAVC 2000).*

CNG buses have substantially lower particulate matter emission rates than diesel buses. These difference in these rates may become less in response to the 2004 and 2007 government emission limits. For at least one CNG-powered bus, the PM emission rate was found to be below the limits of measurement, as was the case with some of the hybrid diesel-electric buses.

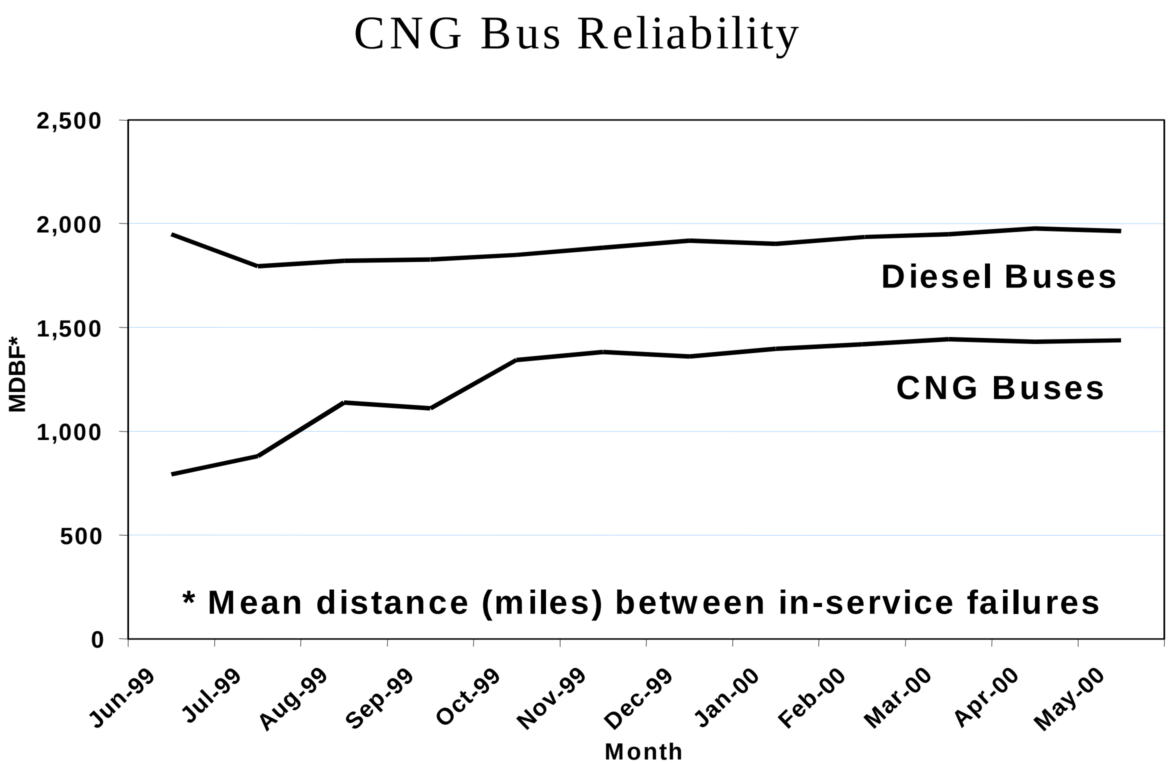
CNG buses, compared with diesel buses, offer moderate NOx reductions. However, the emissions performance of CNG buses is sensitive to fuel system calibration. The dynamometer emission data document an instance of high NOx emission rates, a problem that will hopefully be minimized with emerging electronic fuel metering systems.

CNG buses have CO_2 emission rates that are somewhat lower than those of diesel buses, and somewhat higher than those of hybrid diesel-electric buses. This results from a trade-off between the naturally lower carbon content of CNG, as compared to diesel fuel, and the somewhat lower fuel economy for the CNG buses.

Reliability

In New York City, CNG buses are about 50 to 75% as reliable as comparable diesel buses in revenue service. The NYCT experience, shown in Figure 5 (p. 20), indicates an average mean distance between failures (MDBF) of about 1,500 miles as compared with 2,000 miles for diesel buses (Lowell, 2000B).

FIGURE 5. COMPARATIVE RELIABILITY OF COMPRESSED NATURAL GAS (CNG) AND DIESEL BUSES, IN A RECENT NEW YORK CITY TEST (LOWELL 2000B)



Costs

Costs for fueling facilities, garage modifications including greater safety protection, buses, and operations are higher for CNG than for diesel buses. CNG requires special fueling facilities and associated changes within maintenance garages. Should other propulsion technologies emerge in the future (e.g., fuel cells), the investment in CNG infrastructure would be lost.

Garage and Maintenance Facility Costs: TCRP Report 38 cites the following typical capital costs for fueling facilities and maintenance facility modifications (Table 13):

TABLE 13. TYPICAL CAPITAL COSTS FOR FUELING FACILITIES AND MAINTENANCE FACILITY MODIFICATION

No. of Buses	Fueling Facilities	Maintenance Facility Modifications	Total
10	$ 275,000	$125,000	$ 400,000
50	$575,000	$225,000	$800,000
200	$1,700,000	$600,000	$2,300,000

Even higher costs are reported from the experience of large transit systems (Table 14):

TABLE 14. TYPICAL CAPITAL COSTS FOR FUELING FACILITIES AND MAINTENANCE FACILITY MODIFICATION IN LARGE TRANSIT SYSTEMS

Transit System	Fueling Facility	Maintenance Facility Changes	Total
Cleveland	$3,000,000	$750,000	$3,750,000
Los Angeles	$5,000,000	$1,000,000	$6,000,000
New York City (per depot)	$5,000,000	$10,000,000 - $40,000,000	$15,000,000 - $50,000,000

The relatively high New York City costs for maintenance facility changes are due in part to the multi-level nature of the NYCT garages.

Vehicle Costs: The costs for CNG buses typically exceed those for diesel buses. *TCRP 38* cites costs of $250,000 for diesel and $320,000 for CNG, a 28% difference. The General Accounting Office (GAO 1999) report cites costs of $250,000 to $275,000 for a typical diesel bus and $290,000 to $318,000 for CNG buses — a difference of 15 to 25%. Several factors account for these higher purchase costs, including the precision needed to engineer and manage light, durable and reliable on-board CNG tanks; the liability cost associated with defects in tank design and manufacture; and the need for onboard fire protection systems.

Fuel and Maintenance Costs: The fuel cost per bus mile depends upon the relative price of diesel fuel and CNG at any point in time and geographic location, and the extent that special arrangements can be made with local natural gas companies or distributors. In 1996-98, when *TCRP Report 38* was prepared, fuel costs for each approximated $0.20 per bus mile. Since then, the cost of both natural gas and diesel fuel has increased substantially.

Three of six transit agencies contacted by the GAO (presumably before December 1999) reported their costs for CNG fuel exceeded that for diesel fuel, one (St. Louis) reported that its costs were the same, and two reported that their costs were lower. More recent information furnished by NYCT indicated that CNG fuel costs were $0.16 per mile greater than those for diesel fuel.

TCRP Report 38 cited a fuel-related maintenance cost of $0.46 per mile for CNG and $0.40 for diesel — a difference of $0.06 per mile. NYCT indicates that it costs an additional $0.20 per mile to maintain CNG buses.

Assessment

At present, CNG is the most widely proven and available alternative fuel for transit buses in revenue service. CNG buses can work well in revenue service; they are the most popular clean-fuel option; and their emissions are lower than those of conventional diesel buses. However, they are about 40% less energy efficient than diesel buses in urban service; they are significantly more expensive to operate than diesel buses; and they require additional infrastructure.

Hybrid Diesel-Electric Propulsion

Hybrid diesel-electric propulsion is a promising new technology that can reduce emissions without requiring substantial new investments in infrastructure. Prototypes have been developed; a few are in revenue service and more have been ordered. Their use is expected to increase during the next decade. These hybrid buses offer the following advantages:

- very low emissions, especially when operated on ultra-low-sulfur (<50 ppm) fuel
- excellent fuel efficiency, especially in frequent-stop, urban service
- excellent acceleration from a complete stop
- no significant changes in the present infrastructure

However, they have these disadvantages:

- somewhat high initial vehicle cost
- relatively new technology
- availability / reliability issues, especially for the batteries
- limited availability
- reduced fuel economy at high speeds

Nevertheless, because of the demonstrated advantages of these buses at the time of this report, we expect this propulsion technology to become a significant factor in the next several years.

Status

Hybrid electric buses are in demonstration use around the globe today and have become commercially available in the last year. *TCRP Report 59*, "Hybrid Electric Transit Buses: Status, Issues and Benefits," estimates that there were 300 hybrid buses worldwide as of 1999, of which about 70 have been, or are being, tested in the United States.

FIGURE 6. PHOTOGRAPH OF AN ORION/LOCKHEED HYBRID DIESEL-ELECTRIC BUS. THIS BUS IS OF THE SERIES STYLE.

In the United States, demonstrations are underway in New York City, Cedar Rapids (Iowa) and Los Angeles, and have been planned or are in process in several other cities. NYCT tested an Orion/General Electric prototype in 1996. Five 40-passenger Orion/Lockheed buses entered revenue service in September 1998, and the NYCT has received five more that have been placed in revenue service. Five Nova/Lockheed buses were delivered and placed in service in late 2000. An additional 125 Orion/Lockheed buses have been ordered for delivery starting in late 2001. Collectively, these vehicles will account for about 3% of NYCT's 40,000-bus fleet. The Orion/Lockheed hybrid bus operating in New York City is shown in Figure 6 (p. 22).

Principle of Operation

The propulsion system for hybrid diesel-electric buses consist of a conventional diesel fuel engine, a generator / alternator driven by the engine, a control system, a substantial battery, and an electric motor that powers the bus. In operation, the engine provides power to charge the battery, operate the bus indirectly through the control system and motor (see Figure 7A), and in some systems, also drive the bus directly (see Figure 7B).

FIGURE 7A. SKETCH ILLUSTRATING THE OPERATION OF A SERIES STYLE DIESEL-ELECTRIC HYBRID POWERED BUS.

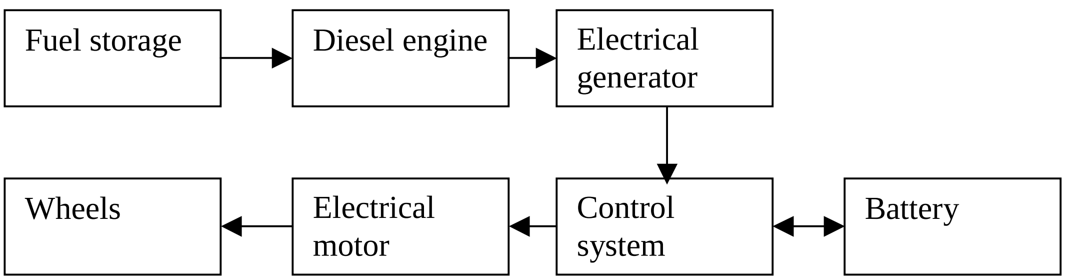
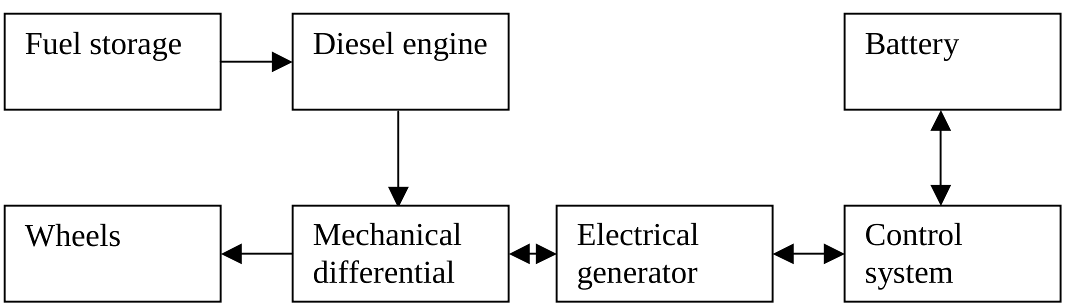


FIGURE 7B. SKETCH ILLUSTRATING THE OPERATION OF A PARALLEL STYLE DIESEL-ELECTRIC HYBRID POWERED BUS



Hybrid electric buses allow much of the vehicle's braking to be accomplished electrically with no mechanical wear. Maintenance costs for transmission and brake repairs, substantial in conventional transit buses, could be reduced. Regenerative braking conserves energy. Using a properly rated diesel engine, energy consumption and emissions can be 30 to 50% lower than for diesel buses.

Emissions

Hybrid and conventional diesel bus emissions are compared in Table 15 for the typical Combined Business District (CBD) bus cycle. The reduction in emissions from hybrid buses vs. conventional is indicated by the "Delta" column. Tables 16 and 17, in turn, compare emissions for diesel, hybrids and CNG buses for both the CBD and New York bus cycles. The hybrids achieve substantial reductions in emissions as compared with the standard diesel buses, and are generally comparable to (and often lower than) CNG buses in emissions levels.

TABLE 15. HYBRID BUS EMISSIONS (*TCRP 59*)

Emission	**Conventional**[1]	**Hybrid**[2]	**Delta**
PM			
g/mile	0.24	0.12	0.12
ton/year/bus[3]	0.01	0.00	0.00
NO_x			
g/mile	30.1	19.2	10.9
ton/year/bus	0.89	0.57	0.3
ton/year/100 buses	89.40	57.02	32.4
VOC			
g/mile	0.14	0.08	0.1
ton/year/bus	0.00	0.00	0.0
ton/year/100 buses	0.42	0.24	0.2
CO			
g/mile	3.0	0.1	2.9
ton/year/bus	.09	0.00	0.1
ton/year/100 buses	8.91	0.30	8.6
CO2			
g/mile	2,779.0	2,262.0	517.0
ton/year/bus	82,54	67.18	15.4
ton/year/100 buses	8,253.63	6,718.14	1,535.5

SOURCE: NAVC, WVU, MJBradley & Associates & *Air Daily*
NOTE: VOC = Volatile Organic Compounds

[1] Nova BUS RTS with MY 1999 Series 50 engine and Diesel #1 fuel.
[2] Orion Hybrid V1 with MY 1998 Series 30 engine and Diesel #1 fuel.
[3] Assumes 27,000 miles / bus and conversion factor for 1 (short) ton = 908,000 grams.

TABLE 16. SUMMARY OF BUS EMISSIONS FOR THE COMBINED BUSINESS DISTRICT (CBD) BUS CYCLE.. ALL EMISSIONS ARE GIVEN IN GRAMS PER MILE (*NAVC 2000*)

	PROPULSION			
EMISSION	**DIESEL**	**CNG**	**HYBRID**	**HYBRID WITH ULTRA-LOW-SULFUR FUEL AND CRT™**
PM	0.24	0.02	0.12	0.02
NO_x	30.1	10-25	19.2	18.5
CO	3.0	0.6-13	0.1	0.1
CO_2	2779	2400	2262	2218
NMOC	0.14	0.6-3.15	0.08	0.03

TABLE 17. SUMMARY OF BUS EMISSIONS FOR THE NEW YORK (NY) BUS CYCLE. ALL EMISSIONS ARE GIVEN IN GRAMS PER MILE

	PROPULSION			
EMISSION	**DIESEL**	**CNG**	**HYBRID**	**HYBRID WITH ULTRA-LOW-SULFUR FUEL AND CRT™**
PM	0.70	bdl-0.14	0.16	bdl
NO_x	72	15-113	40.5	32
CO	11	28-37	5.0	0.1
CO_2	7076	5610-6535	4251	3930
NMOC	0.6	3.35-4.84	1.13	0.5

The NAVC studies summarized in the two tables above indicate that hybrids have:

- much lower PM emissions, as compared to a standard diesel bus, below the detectable limit (bdl) in some cases;
- about 45 to 65% of the NOx emissions of a standard diesel bus; generally comparable to CNG buses;
- significantly lower CO emissions than either diesel or CNG buses; and
- about 60 to 75% the greenhouse gas emissions of a CNG bus, and about 75 to 80% those of a diesel bus.

The diesel-electric hybrid bus has better fuel economy than conventional diesel or CNG buses, especially under low speed conditions. NYCT, for example, reports that hybrids operating in Manhattan get 24% more miles per gallon. The North American Vehicle Consortium (NAVC) shows that hybrids (especially with regenerative braking) get more miles per gallon than conventional diesel or CNG buses (see Table 18, p. 26).

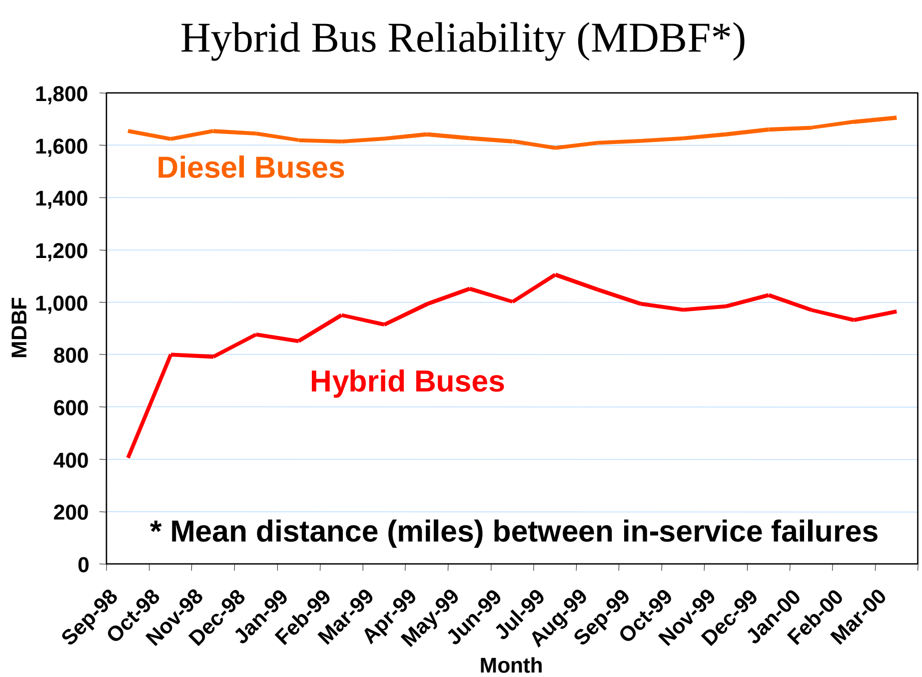
TABLE 18. FUEL ECONOMY FOR SEVERAL BUS PROPULSION TECHNOLOGIES AND SEVERAL DIFFERENT BUS OPERATION CYCLES

REPORTED FUEL ECONOMY (Miles per Gallon)			
PROPULSION	**BUS CYCLE**		
	CBD	New York	Manhattan
Hybrid (Orion)	3.7-4.3	1.5-2.3	3.4
Diesel	3.5	1.4	2.3
CNG	2.6-3.1	1.1-1.3	2.1

Reliability

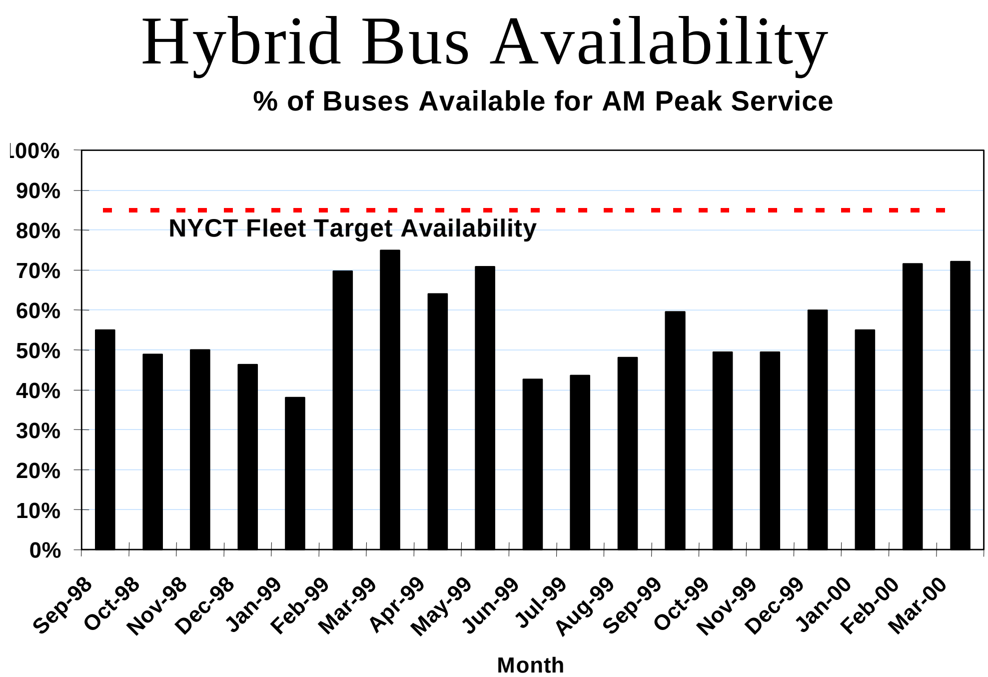
NYCT's hybrid buses have achieved a reasonable level of reliability, especially given the relatively new state of this technology. The NYCT hybrid buses have an average mean distance between in-service failures (MDBF) of more than 1,000 miles as compared with about 1,700 for the conventional diesel (59% of the diesel MDBF; see Figure 8). It should, however, be pointed out that for the first year of NYCT CNG operation (November 1995 to October 1996), the CNG buses had an MDBF rate that was 62% of the diesel value.

FIGURE 8. COMPARISON OF THE RELIABILITY OF HYBRID DIESEL-ELECTRIC BUSES TO THAT OF CONVENTIONAL DIESEL BUSES IN NEW YORK CITY REVENUE SERVICE (*LOWELL 2000A*)



NYCT has established a criterion of 80% in-service availability for A.M. peak service. NYCT's hybrid buses have achieved an average availability rate of about 55% and at times as high as 75%, or close to that of its diesel fleet (Figure 9). NYCT expects the hybrids to catch up with diesel buses in reliability as hardware and software issues found during the first 13 months of operation are corrected.

FIGURE 9. A COMPARISON OF THE AVAILABILITY OF HYBRID DIESEL-ELECTRIC BUSES AND DIESEL BUSES, IN A RECENT NEW YORK CITY TEST (LOWELL-2000C)



Costs

The costs for hybrid-electric buses include infrastructure costs, fuel and maintenance. These costs, as set forth in *TCRP 59*, are given in Tables 19 through 21 (pp. 28-29). Table 22 (p. 30) in turn gives total annual bus costs for infrastructure, vehicles, fuel, and maintenance.

Infrastructure Costs: One of the advantages of hybrid technology, and the diesel-electric hybrid in particular, is that it enables a transit agency to achieve significant reductions in emissions without major investments in new fueling infrastructure. This advantage is apparent from Table 19 (p. 28), which gives the ranges in infrastructure costs for a 100-bus fleet of diesel hybrid buses. This fleet can be integrated into an existing bus garage for less than $200,000 in infrastructure modifications — about $2,000 per bus. Most of this expense would be for electrical equipment and wiring associated with battery equalization.

Vehicle Costs: Hybrid electric transit buses are available, but at substantially higher costs than conventional diesel buses (see Table 20, p. 28). However, costs are likely to decrease depending upon the number of buses produced. For example, for small volumes (5-10 buses), costs would range from $440,000 to $840,000 per bus, while the mid-volumes (100 or more) buses would cost

TABLE 19. HYBRID BUS INFRASTRUCTURE COSTS (*TCRP 59*)

Per 100 Hybrid buses	Hybrid (Low)	Hybrid (High)
Diagnostic equipment[1]	$ 5,000	$ 10,000
Battery handling & charging	$ 5,000[2]	$ 135,000[3]
Electrical service upgrades	$ 5,000[4]	$ 25,000[5]
TOTAL $/100 bus fleet	$ 15,000	$170,000
$/bus/year[6]	$ 10	$113
$/bus/mile	$ 0.00	$ 0.01

SOURCE: NYC Transit & Orion.

TABLE 20. HYBRID TRANSIT BUS VEHICLE COSTS (*TCRP 59*)

Volume	Conventional Drive	Hybrid (High)[7]	Hybrid (Low)[8]	Delta (High)	Delta (Low)
Small volume (5-10)					
$/unit	$ 280,000	$ 840,000	$ 440,000	$560,000	$ 160,000
$/mile[9]	0.69	2.07	1.09	1.38	0.40
Mid volume (100+)					
$/unit	280,000	$450,000	$385,000	$ 170,000	$ 105,000
$/mile[9]	0.69	1.11	0.95	0.42	0.26
Production (1,000+)					
$/unit	$ 280,000	$350,000	$ 280,000	$70,000	$ -
Annual $/unit	$ 18,667	$23,333	$18,667	$4,667	$ -
Annual $/unit/mile[9]	0.69	0.86	0.69	0.17	-

1 Includes laptop computers & high impedance multimeter.
2 Charger included in price of bus and existing forklift used to remove batteries
3 Fast chargers purchased and overhead crane installed to remove batteries
4 Install electrical outlets, 208 VAC, 50 amp. 3-phase service
5 Install 480 VAC service and load management equipment
6 Assumes 15 year life
7 Assumes significant truck market penetration and economies of scale (100k units / year
8 Assumes hybrids do not achieve economies of scale, and production <10K units / year.
9 Based on 15 year life of 27,000 miles per year.

from $385,000 to 450,000. For higher rates of production, costs would approach parity with diesel buses. The recent NYCT purchase was for 125 hybrid buses at $385,000 per bus. Assuming a 400,000-mile service life per bus, mid-volume costs per bus mile would range from $0.95 to $1.11, compared with $0.69 for conventional diesel buses.

Maintenance Costs: Hybrid maintenance costs in revenue service are yet to be determined. Current estimates, shown in Table 21, suggest that the maintenance costs per bus mile could be up to $0.16 more or less than for conventional diesel buses.

TABLE 21. HYBRID BUS MAINTENANCE COSTS (*TCRP 59*)

Component	Hybrid vs. Mechanical (+/-)	Cost Delta
Engine	n/c	TBD
Generator	+	TBD
Traction Motor	+	TBD
Transmission	-	TBD
Traction Batteries	+	TBD
Mechanical Brakes	-	TBD
Net Change	TBD	TBD
$/mile Diesel bus[1]	$ 1.60	$ -
$/mile Hybrid (High)[2]	$ 1.76	$ 0.16
$/mile Hybrid (Low)[3]	$ 1.44	$ (0.16)

Fuel Costs: Fuel costs per bus mile reported in *TCRP 59* were as follows:

- Diesel $0.21
- Hybrid High $0.29
- Hybrid Low $0.21

Note that these reported fuel costs include regular fuel expenses plus assorted battery costs, which apparently offset the improved mileage as reported for hybrid bus propulsion in Table 18 (p. 26).

Total Costs. Total annual costs for a 100-bus diesel-electric bus system are shown in Table 22 (p. 30). These costs are based on 27,000 bus miles per year and a 15-year service life, or about 400,000 bus miles. The total costs per bus, per year range from about $63,000 to $79,000 for hybrids as compared with about $67,000 for conventional diesel buses. The costs per bus mile are $2.50 for conventional diesel and $2.33 to $2.92 for the hybrid.

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[1] Baseline diesel bus maintenance cost provided by MBTA.

[2] Assumes 10% increase in maintenance costs.

[3] Assumes 120% decrease in maintenance costs.

TABLE 22. HYBRID BUS ANNUAL COST SUMMARY (*TCRP 59*)

Per bus/year	Conventional diesel	Hybrid (High)	Hybrid (Low)	Delta (High)	Delta (Low)
Vehicles	$ 18,667	$23,333	$18,667	$ 4,667	$ -
Fuel	$ 5,554	$ 7,861	$ 5,653	$ 2,307	$99
Maintenance	$ 43,200	$ 47,520	$ 38,880	$ 4,320	$ (4,320)
Infrastructure	$ -	$ 113	$ 10	$ 113	$ 10
Emissions	$ -	$ -	$ (329)	$ -	$ (329)
Total	$ 67,421	$ 78,828	$ 62,881	$ 11,407	$ (4,540)
Per 100 buses	$ 6,742,095	$ 7,882,800	$ 6,288,092	$ 1,140,705	$ (454,005)
Per bus mile	$ 2.50	$ 2.92	$ 2.33	$ 0.42	$(0.17)

The NYCT operating experience of more than 110,000 revenue miles indicates that the hybrid bus to date compares favorably with other new technologies. The operation is quiet, affords excellent acceleration and smooth operation and requires little or no operator training. These buses do not roll back on hills.

Operating benefits are greatest in low-speed environments such as in Manhattan. Conversely, buses can have difficulty maintaining sustained high speeds (as is common on CT -Transit express runs), and in maintaining speeds on long, sustained grades. In these cases, fuel economy is lost.

Diesel-electric hybrids are available in traditional 40-foot bus lengths; however articulated hybrids remain unavailable. Small CNG hybrids operate in several cities, but usually as shuttles.

NYCT found that battery equalization and periodic battery conditioning are both required to optimize reliability. Catalytic exhaust filters are being redesigned and exhaust temperature and back pressure are being monitored to optimize emissions and reliability.

Assessment

Hybrid electric-drive transit buses have the ability to improve fuel economy, reduce emissions, and lower maintenance and operating expenses. They require little infrastructure modifications (in contrast to CNG buses). Vehicle costs are substantially higher at present than for conventional diesel buses, but may go down as the buses are mass produced.

Operating experience — mainly limited to NYCT — compares favorably to date with other new technology introductions. Reliability is presently less than for diesels, but may be improved by monthly battery conditioning to extend battery life and battery equalization. The buses work best in urban environments, with frequent starts and stops, and with relatively low average speeds (10 to 15 mph). The inability to effectively maintain speed on steep grades or to operate cost effectively in express operations must be recognized in their application.

Fuel Cells

Fuel cell-powered buses offer these advantages:

- very low levels of emissions, including all greenhouse gases (hydrogen-powered buses only)
- very low levels of emissions for all pollutants except carbon dioxide, for hydrocarbon-powered buses
- overall efficiencies of up to 40%
- very quiet operation

However, these buses have the following disadvantages:

- very high purchase cost
- very limited in-service operation
- yet to be determined availability and reliability
- yet to be established commercial sources
- limited range with currently available compressed hydrogen systems
- large physical size for systems that use hydrocarbon fuel

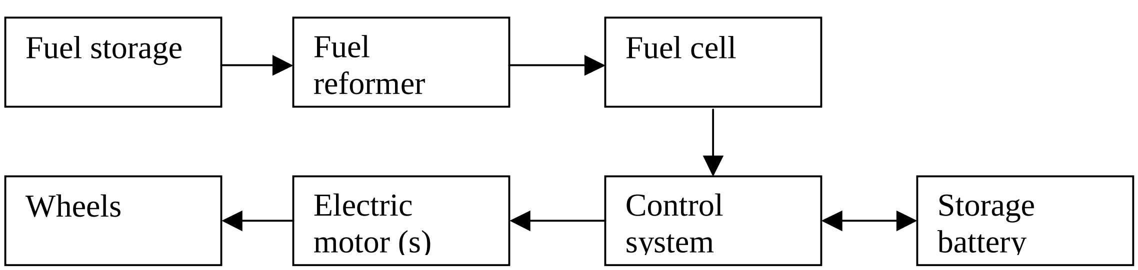
Status

A few battery-propelled buses are in service in the United States and abroad. However, these vehicles have very short operating ranges. Fuel cell-powered buses for conventional transit service are under development, and could be viable within the decade.

Principle of Operation

Fuel cell propulsion systems (Figure 11) consist of the fuel cell (which consumes hydrogen and generates electrical power), a battery, a control system, and a motor(s) to drive the wheels. Also, if the on-board fuel is anything other than hydrogen, a chemical reformer is needed to convert the hydrocarbon fuel into hydrogen.

FIGURE 11. SKETCH ILLUSTRATING THE OPERATION OF A FUEL CELL-POWERED BUS. NOTE THAT THE FUEL REFORMER IS NEEDED ONLY FOR HYDROCARBON FUEL-POWERED BUSES, AND NOT FOR HYDROGEN-POWERED BUSES.



Emissions

The direct emissions from a fuel cell-powered bus can be very low. If the on-board fuel is hydrogen, then the only significant emission is water vapor. If the on-board fuel has a carbon content (natural gas, methanol, ethanol, gasoline), then the fuel-reforming process will result in significant CO_2 emissions, with small amounts of other gases.

Reliability

It is too early in the technology cycle to discuss reliability of fuel cells for transit bus operation. Fuel cell-powered buses will likely have very different failure modes than other buses. For example, the failures associated with internal combustion engines are absent. However, fuel cells (and the associated fuel reformer) are very sensitive to impurities in the fuel, especially to materials such as sulfur.

Costs

Costs are very high at the present time. However, because of the potential of this technology to create buses with very low emissions and quiet operation, considerable research and development is in progress, in efforts to lower the costs and to establish the reliability for this technology.

Assessment

Because fuel cell-powered buses offer the potential for extremely low emission vehicles, there is considerable enthusiasm for this technology, and considerable development efforts are in progress. A consensus opinion (NAVC 2000B) from 44 experts on the future of this technology concluded that fuel cell-powered buses would become a viable and interesting possibility in the latter half of this decade. Therefore, CONN-DOT and CTTRANSIT™ should monitor this technology, with the possibility of incorporating these buses into the fleet as the technology matures.

SYNTHESIS AND IMPLICATIONS

In an attempt to reduce bus emissions, many bus propulsion systems have been used as an alternative to the conventional diesel buses that continue to dominate the bus fleet. Of these, CNG buses have been the most widely used. Several other low-emission bus technologies — diesels with low-sulfur fuel and diesel-electric hybrids with regular and low-sulfur fuel — have emerged in the last few years, and have been placed in revenue service. Both avoid the infrastructure costs and potential safety concerns associated with CNG, although hybrid vehicle costs remain substantial. Finally, fuel cells remain on the horizon, and may become a reality by or shortly after 2010.

Accordingly, detailed analyses were made of the costs, emission characteristics and operating aspects of the four likely propulsion methods that have potential large-scale applicability in Connecticut within the next decade. These are (1) conventional diesel, (2) diesel with ultra-low-sulfur fuel, (3) compressed natural gas, and (4) diesel-electric hybrids with and without ultra-low-sulfur fuel.

Comparative Analysis

A comparative analysis of these four propulsion technologies follows. A series of tables give comparative infrastructure costs, vehicle costs, total costs and emissions per bus mile. Costs and emissions relative to diesel buses are used as a base, and costs per emission reduced (incremental costs per bus mile versus incremental emissions reduced in grams/bus mile) are computed.

Table 23 gives comparative infrastructure costs. Note that only CNG involves substantial costs. These costs show considerable variation from city to city.

TABLE 23. COMPARATIVE INFRASTRUCTURE COSTS

PROPULSION	TOTAL $	$ PER BUS MILE[1]
DIESEL	--	--
LOW SULFUR DIESEL	--	--
CNG		
100-bus fleet (*TCRP 38*)	$1,500,000[2]	$ 0.04
200-bus fleet	$2,300,000	$ 0.03
Cleveland	3,750,000[2]	$ 0.09
Los Angeles	6,000,000[2]	NA
New York City	15,000,000 50,000,000[2]	NA
DIESEL ELECTRIC HYBRID		
100-bus fleet low	15,000	Negligible
100-bus fleet high	170,000	Negligible

Table 24 (p. 34) gives comparative vehicle costs. Note that diesel-electric hybrids cost substantially more than other bus technologies. However, these costs are expected to drop as the number of hybrids purchased increases (*TCRP 59*).

[1] Based upon 400,000 miles per bus
[2] Includes Fueling Facilities and Maintenance Facility Changes

TABLE 24. COMPARATIVE VEHICLE COSTS

PROPULSION	TOTAL $	$ PER BUS MILE[1]
DIESEL	$280,000	$0.70
LOW SULFUR FUEL	$285,000[2]	$0.71
CNG	$320,000	$0.80
DIESEL ELECTRIC HYBRID		
LOW	$385,000	$0.96
HIGH	$440,000	$1.10

Table 25 gives incremental fuel costs per bus mile, including both ranges and "likely" costs for CNG and hybrids relative to diesel.

TABLE 25. INCREMENTAL FUEL COSTS PER BUS MILE

Fuel/propulsion type	Additional cost relative to diesel (dollars per bus mile)
Diesel with ultra-low-sulfur fuel	0.04
CNG	0.52
Diesel-electric hybrids	0.45

These cost differences include infrastructure, vehicles, fuel, and maintenance.

Table 26 (p. 35) shows total costs per bus mile. For those cost elements that are given as a range, the values in the brackets were used for analyses discussed later in this report.

1 Based on 400,000 miles per bus
2 Estimated

TABLE 26. COMPARATIVE TOTAL COSTS PER BUS MILE
(IN DOLLARS PER BUS MILE)

COST ITEMS	DIESEL COSTS	DIFFERENCE FROM DIESEL		
		DIESEL/LOW SULFUR FUEL	CNG	DIESEL-ELECTRIC HYBRID
INFRASTRUCTURE 100-BUS FACILITY	--	--	0.04 - 0.09 [.06]	negligible
VEHICLE	0.70	0.01[1]	0.10	0.26 - 0.40 [0.40]
FUEL COSTS	0.21	$0.03[1]	0.16	0.00-0.09 [0.05]
MAINTENANCE COSTS	1.60	0.00	0.06[2] 0.20[3] [0.20]	-0.16 - + 0.16 [0.00]
TOTAL	2.51	0.04	0.36-0.55	0.10 - 0.65
LIKELY VALUE	2.51	0.04	+0.52	0.45

Table 27 gives comparative bus emissions, in grams per mile, for the various bus technologies. For those emission values that are given as a range, the values in the brackets are used for analyses discussed later in this report. These emissions, for the CBD bus cycle, are based on the

TABLE 27. COMPARATIVE BUS EMISSIONS IN GRAMS PER MILE
COMMERCIAL BUSINESS DISTRICT (CBD) BUS CYCLE

EMISSION	PROPULSION SYSTEM				
	DIESEL	DIESEL WITH LOW SULFUR FUEL (and CRT™)	CNG	DIESEL ELECTRIC HYBRID	DIESEL ELECTRIC HYBRID WITH LOW SULFUR FUEL AND CRT™
PM	0.24	0.024	0.02	0.12	0.02
NOx	30.1	28.6	9.7-25 [16.5]	19.2	18.5
NMOC	0.14	0.014	0.6-3.15 [2.0]	0.08	0.03
CO	3.0	0.30	0.6-12.7 [8.0]	0.1	0.1
CO_2	2779.0	2500[1]	2343-2785 [2507]	2262	2218

[1] Estimated
[2] TCRP 38
[3] NYCT

data shown in Appendix A-1 of the NAVC report (*NAVC 2000*). Comparative values are given for PM, NOx, Non-Methane Organic Compounds (NMOC), CO, and CO_2. For CNG-powered buses, a wide range of values was reported, from which values averages of all the data were derived. Also, although not shown on Table 27, only CNG buses reported measurable emissions for methane (CH_4), with a range of 14.6 to 23.7 grams per mile.

Table 28 gives changes in bus emissions, in grams per mile, as compared to diesel. Note that the greatest reductions in particulate emissions are for CNG and diesel-electric hybrids (with ultra-low-sulfur fuel). Also, note that the average emissions for NOx, NMOC, and CO were greater for CNG than for conventional diesel buses. For those cost elements that are given as a range, the values in the brackets are used for analyses discussed later in this report.

TABLE 28. CHANGES IN EMISSIONS COMPARED WITH DIESEL.
ALL VALUES ARE IN GRAMS PER BUS MILE.

EMISSION		DIFFERENCE FROM DIESEL			
	DIESEL (ACTUAL VALUES)	DIESEL WITH LOW SULFUR FUEL AND CRT™	CNG	DIESEL-ELECTRIC HYBRID	DIESEL-ELECTRIC HYBRID WITH ULTRA-LOW-SULFUR FUEL AND CRT™
PM	0.24	-0.22	-0.22	-.12	-.22
NO_x	30.1	- 1.50	-6.1 to - 20.4 [-13.6]	–10.9	–11.6
NMOC	0.14	–0.12	+0.46-3.01 [+1.86]	–0.06	–0.11
CO	3.0	-2.70	-2.4 to +9.7 [+5.0]	-2.9	-2.9
CO_2	2779.0	279	–14 to –436 [-272]	-517	-561
COST DIFFERENCE ($ PER MILE)	--	0.04	0.52	0.45	0.45

Table 29 (p. 37) gives the additional costs per gram of emission removed relative to conventional diesel fuel. Diesel buses using ultra-low-sulfur fuel have the lowest incremental costs per emission removed. For particulate matter, CNG is more cost effective than diesel-electric hybrids using regular diesel fuel; however, diesel-electric hybrids using ultra-low-sulfur fuel are as cost effective as CNG. The use of CNG and diesel-electric hybrids is equally cost effective in reducing NOx. Use of diesel-electric hybrids reduces CO and CO2, while CNG-fueled buses increase these emissions.

TABLE 29. ESTIMATED COSTS PER EMISSION REMOVED .
(DOLLARS PER GRAM OF EMISSION REMOVED)

EMISSION	DIESEL WITH ULTRA-LOW-SULFUR FUEL	CNG	DIESEL-ELECTRIC HYBRID	DIESEL-ELECTRIC HYBRID WITH ULTRA-LOW-SULFUR FUEL
PM	0.18	2.36	3.75	2.05
NOx	0.03	0.03- 0.09 [0.04]	0.04	0.04
NMOC	0.33	Emissions Increase	7.50	4.09
CO	0.01	Emissions Increase	0.16	0.16
CO_2	Negligible	Negligible	Negligible	Negligible

Implications For Connecticut

The preceding analyses have shown that each alternative fuel reduces emissions relative to today's conventional diesel buses. There are, however, differing perspectives regarding the merits of CNG versus improved diesel bus propulsion.

Some proponents of CNG-powered buses believe that these buses are the only real alternative to more conventional diesel buses. These proponents contend that CNG is a readily available domestic fuel, that ultra-low-sulfur diesel fuel may not be commercially available in the timeframe of this study, and that the last generation of regenerative exhaust filters did not work in revenue service.

However, the NAVC studies and the NYCT operating experience and tests suggest otherwise. They indicate that hybrid diesel-electric technology works, and that ultra-low-sulfur is available in the northeast United States.

Moreover, some transit agencies are pursuing hybrids as an alternative to CNG. For example, the Toronto Transit Commission (TTC) which has operated CNG-fueled buses for the past ten years, recently announced that it has decided to look for new environmentally sound transportation options. TTC currently operates 125 CNG-powered buses, but due to the prohibitive cost of building an infrastructure and the rising costs of natural gas fuel, transit officials are looking to different technologies for future transportation needs. TTC officials complained that government subsidies for CNG use have decreased since the program was first implemented. The environmental benefits of CNG have also dropped off as the systems have aged and the equipment has become less efficient. TTC officials said they are considering hybrid diesel-electric technology for the future of Toronto's transportation services. However, particulate matter filters and ultra-low-sulfur diesel are not yet commercially available in many parts of Canada (*Diesel Fuel News: 8/16/00*)

Given Connecticut's operating and safety environment, these comparisons and perspectives clearly indicate that both low-sulfur-fueled diesel buses (with particulate exhaust filters) and hybrid diesel-electric buses (especially with ultra-low-sulfur fuel and exhaust filters) are better suited to Connecticut conditions than CNG-powered buses. Over the next decade, factors such as lower vehicle cost, ability to operate in all environments (i.e., hills, urban inter-city), and the need to operate both regular and articulated vehicles give low-sulfur diesel the edge over hybrids. However, reduced purchase costs (as more transit systems buy them), combined with the use of low-sulfur fuel, makes hybrids a viable option — particularly after further testing in revenue service.

III. BUS PURCHASE OPTIONS

This section describes and analyzes a series of bus purchase options that assume replacement of 200 buses between 2003 and 2008. These purchase scenarios cover diesel, ultra-low-sulfur diesel, diesel-electric hybrids, and CNG, providing CONN-DOT and CTTRANSIT™ a wide range of options.

We restate a point made earlier. The analysis applied here did not focus on the specifics of the emissions technology, as it is developing to meet EPA set standards. Because of the numerous and rapid changes taking place in the development and introduction of emissions-reducing technologies, it was judged that this study could not adequately address the science of emissions and "pick the winners". Rather, the committee has chosen to chart a course for minimizing the fiscal risk of choice.

Each option presented here is based on the assumption that all buses purchased after 2003 meet or exceed the EPA emissions standards as presented in Table 1 (p. 1). Buses that do not meet that standard will not be allowed into the marketplace. Thus, for example, diesel buses operating on regular sulfur content fuel (although much cleaner than a decade ago) would not be acquired after 2004. Conversely, fuel cell-powered buses should be incorporated in any option toward the end of the decade, wherever they: a) have been proven technically viable, b) have operated successfully in revenue service elsewhere, c) have reasonable costs, and d) have no safety problems.

For each option the details of the year-by-year purchases are indicated in table form, keyed to replacing 200 buses over a 6-year period, beginning in 2003. (The purchases for 2001-2002 have already been determined, and are included in the tables for reference only.) Next, costs and emission implications are given. Finally, suggested directions for Connecticut are indicated.

DESCRIPTION OF OPTIONS

Five basic bus purchase options were developed. These are:

A. Conventional diesel buses, using ultra-low-sulfur fuel after 2004
B. All new diesel buses using ultra-low-sulfur fuel
C. Diesel buses and diesel-electric hybrid buses, both using ultra-low-sulfur fuel
D. Diesel-electric hybrid buses using ultra-low-sulfur fuel (accelerated purchase)
E. Diesel and CNG buses

Option A

Conventional diesel buses, with buses purchased after 2004 using ultra-low-sulfur (<50 ppm sulfur) fuel: The purchase scenario for this option is shown in Table 30 (p. 40). In this option, about 33 diesel-powered buses would be purchased in each of six years. In the first two years (2003 and 2004), the buses would use standard low-sulfur fuel (<500 ppm sulfur). Buses purchased in and after 2004 would be fitted with the exhaust gas equipment (e.g., continuously regenerative filters) needed to achieve the then-current emissions requirements, and all buses would be fueled with ultra-low-sulfur fuel. This option would involve minimal risk and minimal cost. The emissions levels for buses purchased after 2004 would conform to all regulations and standards, and these buses would have substantially lower emissions than the buses being replaced. However, from a community perspective, this would be a relatively passive strategy.

TABLE 30. BUS PURCHASE OPTION A, CONVENTIONAL DIESEL WITH ULTRA-LOW-SULFUR DIESEL BUSES AFTER 2004.

Propulsion Method	Year									
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Diesel	40	40	34	34						
Diesel/low sulfur fuel					33	33	33	33		
Hybrid diesel-electric/low sulfur fuel										
CNG										
Fuel Cells										
Totals	40	40	34	34	33	33	33	33		
	Ordered		To be purchased							

Option B

Accelerated use of ultra low sulfur fuel: The purchase scenario for this option is shown in Table 31. In this option all 200 buses would be equipped with continuously regenerative filters. The costs would be only slightly higher than those for option A, and there would be minimal risk. Aggregate emissions would be lower than for option A; however, this option would require almost immediate access to ultra-low-sulfur fuel.

TABLE 31. BUS PURCHASE OPTION B, ACCELERATED LOW SULFUR FUEL DIESEL BUSES

Propulsion Method	Year									
	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Diesel	40	40								
Diesel/low sulfur fuel			34	34	33	33	33	33		
Hybrid diesel-electric/low sulfur fuel										
CNG										
Fuel Cells										
Totals	40	40	34	34	33	33	33	33		
	Ordered		To be purchased							

Option C

Diesel and diesel-electric hybrid buses, both using ultra-low-sulfur fuel. The purchase scenario for this option is shown in Table 32. Over the six year purchase period, some 141 diesel buses and about 59 diesel-electric hybrid buses would be purchased. All of these buses would be equipped with CRT™ systems, and all would use ultra-low-sulfur fuel.

TABLE 32. BUS PURCHASE OPTION C, DIESEL AND DIESEL-ELECTRIC HYBRID BUSES

Propulsion Method	**Year**									
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Diesel	40	40								
Diesel/low sulfur fuel			34	24	23	20	20	20		
Hybrid diesel-electric/low sulfur fuel				10	10	13	13	13		
CNG										
Fuel Cells										
Totals	40	40	34	34	33	33	33	33		
	Ordered		To be purchased							

In this option, the hybrid buses would be purchased between 2004 and 2008. This deferral would give CTTRANSIT™ an opportunity to observe results of the introduction of hybrid technology by other transit systems, as well as allowing it to benefit from improvements in the relatively new technology as well as, quite probably, lower purchase costs (i.e., less than $350K per bus).

This option would cost more than options A or B, and would entail some additional risk associated with using a "new" propulsion system. However, the emissions resulting from this option would be lower than for A or B. In addition, the exercise of this option would place CONN-DOT and CTTRANSIT™ in a pro-active role from an environmental perspective.

Option D

Diesel-electric hybrid buses, using ultra-low-sulfur fuel: The purchase scenario for this option is shown in Table 33 (p. 42). Over the six-year purchase period, 34 diesel buses and 166 diesel-electric hybrid buses would be purchased. All of these buses would be equipped with CRT™ systems and all would use ultra-low-sulfur fuel.

TABLE 33. BUS PURCHASE OPTION D, DIESEL-ELECTRIC HYBRID BUSES

Propulsion Method	Year									
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Diesel	40	40	34							
Diesel/low sulfur fuel										
Hybrid diesel-electric/low sulfur fuel				34	33	33	33	33		
CNG										
Fuel Cells										
Totals	40	40	34	34	33	33	33	33		
	Ordered		To be purchased							

This option would result in the maximum reduction in emissions. However, it would cost more than the preceding options. It is included for reference only, in view of the uncertainties concerning the reliability of diesel-electric hybrid buses, and because of the operational issues that would be encountered on express service and on routes with steep hills.

Option E

Diesel and Compressed Natural Gas (CNG) buses: This option is shown in Table 34. Some 34 diesel buses would be ordered in 2003, and 166 CNG buses ordered from 2004 to 2008. This purchase option would result in significantly reduced emissions: CNG represents a “clean-fuel” technology that has been used in about 20% of the U.S. bus fleet, and that has been proven to be technically feasible. A first-year purchase of diesel buses is included to enable the installation of the infrastructure that would be needed for CNG operation.

TABLE 34. BUS PURCHASE OPTION E, COMPRESSED NATURAL GAS (CNG) BUSES

Propulsion Method	Year									
	2001	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
Diesel	40	40	34							
Diesel/low sulfur fuel										
Hybrid diesel-electric/low sulfur fuel										
CNG				34	33	33	33	33		
Fuel Cells										
Totals	40	40	34	34	33	33	33	33		
	Ordered		To be purchased							

However, costs would be higher than with other options, because (a) the buses cost more than conventional diesel buses, (b) one or more Connecticut garages would have to be modified for CNG use, and (c) a new fueling infrastructure would be required.

From an operational perspective, there are several significant disadvantages., including the fact that the CNG buses would have to be concentrated in one garage (e.g., a new New Haven garage) and could not be transferred from one operating division to another.

COST AND EMISSION COMPARISONS

The capital and fuel-related operating costs for the five options were developed for the six-year analysis period and compared with the emissions data. The steps in this analysis are as follows:

1. The costs and emissions for conventional diesel buses were used as a base.
2. For each option, the incremental costs and emissions were derived on a per bus-mile basis.
3. The incremental costs and emissions were then summed over the six-year analysis period.

The cost and emission parameters were generally similar to those used for the comparative analyses in Chapter II. However, the costs of the diesel-electric hybrid were adjusted downward from the range of $440,000 –$385,000 to $330,000 to reflect mass purchases of these vehicles (per S. Warren, CTTRANSIT™, private communication). All costs shown were expressed in year 2000 constant dollars.

Capital Costs

The estimated infrastructure and vehicle costs for the five bus purchase options are shown in Table 35 (p. 44). These cost estimates were based upon the values given in Tables 23 and 24. They represent the actual capital costs incurred to make garage changes, and to purchase vehicles over the six-year period.

TABLE 35. ESTIMATED CAPITAL COSTS FOR THE FIVE BUS PURCHASE OPTIONS (ALL COSTS ARE EXPRESSED IN THOUSANDS OF DOLLARS)

Option	Item	Number	Unit cost	Total
A	Infrastructure	None		
	Diesel buses	68	280	19,040
	Diesel buses with ultra-low-sulfur fuel	132	285	37,620
	Total			**56,660**
B	Infrastructure	None		
	Diesel buses with ultra-low-sulfur fuel	200	285	57,000
	Total			**57,000**
C	Infrastructure	1	100	100
	Diesel buses with ultra-low-sulfur fuel	141	285	40,185
	Diesel-electric hybrid buses	59	330	19,470
	Total			**59,755**
D	Infrastructure	1	150	150
	Diesel buses	34	280	9,520
	Diesel-electric hybrid buses	166	330	54,780
	Total			**64,450**
E	Infrastructure	1	3,000	3,000
	Diesel buses	34	280	9520
	CNG buses	166	320	53,120
	Total			**65,640**

Sources: Tables 23 and 24

Total Costs

The comparative differences in total costs per bus mile, as compared to diesel, are shown in Table 36. These cost differences include infrastructure, vehicles, fuel and maintenance. This table is generally similar to Table 26, except that: (a) the diesel fuel costs have been increased to $0.28 cents per mile to reflect current CTTRANSIT™ costs; (b) the diesel-electric hybrid vehicle cost difference was reduced to 13 cents per mile, to reflect the lower anticipated purchase price of buses; and (c) the infrastructure costs for CNG buses was reduced to $0.05 per bus mile to reflect a larger facility size.

TABLE 36. COMPARATIVE COSTS PER BUS MILE FOR SEVERAL PROPULSION TECHNOLOGIES, WITH CONVENTIONAL DIESEL AS A REFERENCE.
ALL VALUES ARE GIVEN IN DOLLARS, AND ARE SHOWN FOR A 100-BUS FLEET, EXCEPT AS NOTED.

Cost item	Diesel costs	Increment from diesel for diesel with ultra-low-sulfur fuel	Increment from diesel for diesel-electric hybrid with ultra-low-sulfur fuel	Increment from diesel for CNG
Infrastructure	0.00	0.00	0.00	0.05 (**a**)
Vehicle	0.70	0.01	0.13	0.10
Fuel	0.28 (**b**)	0.03	0.05	0.16
Maintenance	1.60	0.00	0.00	0.20
Totals	2.58	0.04	0.18	0.51

Source: Adapted from Table 26

(a) Reduced to reflect a 166 bus fleet
(b) Increased to reflect CTTRANSIT™ fuel prices, year 2000

The resulting cost differences per bus mile, relative to diesel, are as follows:

Propulsion technology	Cost differential (cents/bus mile)
Diesel	0
Diesel with ultra-low-sulfur fuel	4
Hybrid with ultra-low-sulfur fuel	18
CNG	51

These cost differences were then applied to the number of bus miles involved for each type of propulsion over the six-year period for each bus purchase option. It was assumed that during this period, the buses would travel 200,000 miles, or half of their expected 400,000 mile lifetime. Thus, the unit cost increases per bus mile for the buses purchased in the first year were multiplied by the number and type of buses acquired and the number of miles involved (i.e., 200,000). The incremental costs for the buses purchased in the sixth year were multiplied by the number of buses acquired and the number of miles involved (i.e., 33,333). The total incremental costs were then accumulated for each option. The results are summarized in Table 37.

TABLE 37. ESTIMATED INCREASES IN TOTAL BUS COSTS FOR THE 2003 TO 2008 PURCHASES, AS COMPARED TO CONVENTIONAL DIESEL.

Option	Cost increase over diesel ($)
A. Conventional diesel, using ultra-low-sulfur fuel after 2004	440,000
B. All new diesel buses using ultra-low-sulfur fuel	939,000
C. Diesel buses and diesel-electric hybrid buses using ultra-low-sulfur-fuel	1,544,000
D. Diesel-electric hybrid buses using ultra-low-sulfur fuel	3,000,000
E. CNG buses	8,500,000

Source: Computed

Emissions

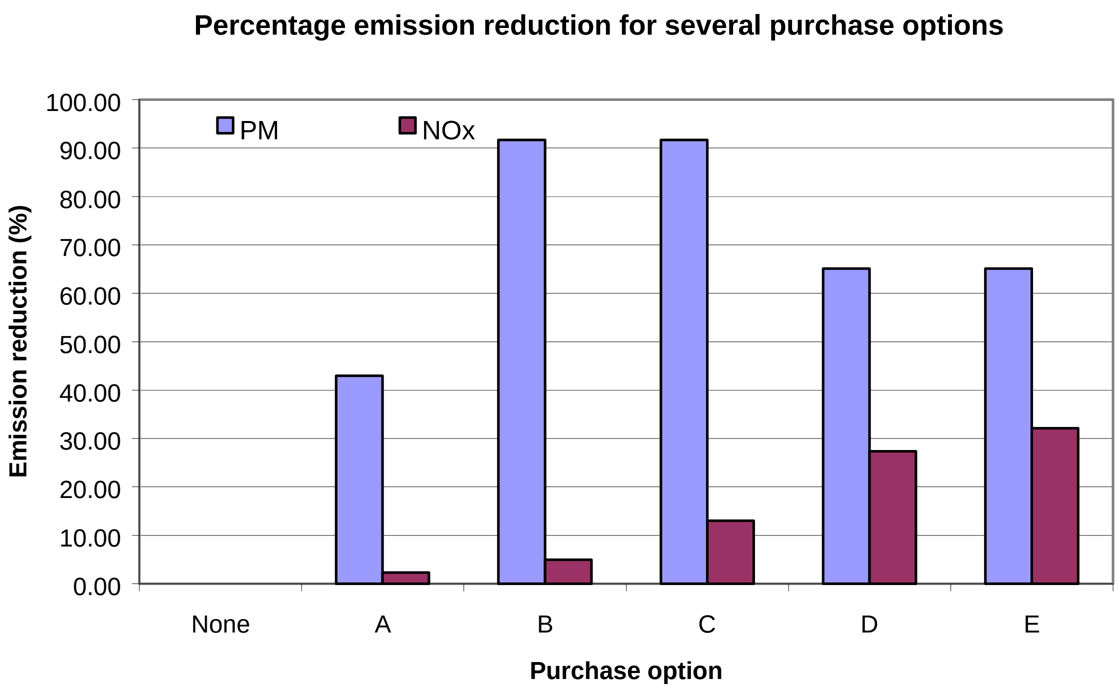
The estimated differences in emissions, as compared to present-day conventional diesel operations, are shown in Table 38. This table is similar to Table 27. Note that for CO and NMOC, CNG results in increased emissions. For those emission values that are given as a range, the value in the brackets will be used for analyses discussed later in this report.

TABLE 38. CHANGES IN EMISSIONS AS COMPARED WITH DIESEL. ALL VALUES ARE IN GRAMS PER BUS MILE.

EMISSION		DIFFERENCE FROM DIESEL			
	DIESEL (ACTUAL VALUES)	DIESEL WITH LOW SULFUR FUEL AND CRT™	CNG	DIESEL-ELECTRIC HYBRID	DIESEL-ELECTRIC HYBRID WITH ULTRA-LOW-SULFUR FUEL AND CRT™
PM	0.24	-0.22	-0.22	-.12	-.22
NOx	30.1	- 1.50	-6.1 to -20.4 [-13.6]	–10.9	–11.6
NMOC	0.14	–0.12	+0.46-3.01 [+1.86]	–0.06	–0.11
CO	3.0	-2.70	-2.4 to +9.7 [+5.0]	-2.9	-2.9
CO_2	2779.0	279	–14 to –436 [-272]	-517	-561
DIFFERENCE IN COST DOLLARS PER MILE	--	0.04	0.52	0.45	0.45

The percentage reductions in particulate matter and NOx are shown in Figure 12 for each option. These reductions were calculated by multiplying the number of buses purchased by the emissions reduction per bus and by the number of miles of total revenue service over the 2003-2008 time frame.

FIGURE 12. PERCENTAGE REDUCTION IN EMISSIONS FOR THE BUS PURCHASE OPTIONS DISCUSSED IN THIS REPORT.



The total emissions savings over the six-year analysis period for each option were then obtained by relating the emissions savings in each option to the total bus miles involved for each of the bus purchase options. The unit reduction (or increase) for each type of emission per bus mile was multiplied by the number and type of buses acquired in each of the six years and the number of bus miles involved. The results of these computations, expressed in total tons of emissions reduced are shown in Table 39 (p. 48), along with the total increases in cost.

TABLE 39. RELATED COST INCREASES AND EMISSIONS REDUCTIONS OVER CONVENTIONAL DIESEL BUS OPERATION

		6 Year Emissions Reductions in Tons				
Option	Cost increase over diesel ($000)	PM	NOx	NMOC	CO	CO2
A. Conventional diesel, using ultra-low-sulfur fuel after 2004	440	-2.66	-18.17	-1.45	-32.7	-3378.69
B. All new diesel buses using ultra-low-sulfur fuel	939	-5.68	-38.76	-3.1	-69.77	-7209.36
C. Diesel buses and diesel-electric hybrid buses using ultra-low-sulfur-fuel	1,544	-5.69	-101.09	-3.04	-71.03	-8952.09
D. Diesel-electric hybrid buses using ultra-low-sulfur fuel	3,000	-4.04	-212.98	-2.02	-53.24	-10299.96
E. CNG buses	8,500	-4.04	-249.7	34.15	91.8	-4993.92

Cost-effectiveness

The estimated cost per ton of particulate matter (PM) and NOx reduced are shown in Table 40.

TABLE 40. COST PER TON OF EMISSIONS REDUCED ($K PER TON)

OPTION	PM	NOx
A	165	24
B	165	24
C	271	15
D	743	14
E	2104	34

RECOMMENDED ACTIONS:

The following recommended actions emerge from the preceding comparisons. They are designed to reduce emissions, match service and market needs, reduce risk, and minimize cost. They all permit contemporary low-floor design.

***First choice* - Option C, a mix of state-of-the-art diesel buses and hybrid diesel-electric buses.**

The study committee believes that this option represents the best balance between:

- aggressively pursuing lower emission levels
- striving for cost-effective mixes, and
- maintaining a fleet of reliable, available buses

This fleet mix matches the mixed market needs of CONN-DOT and CTTRANSIT™. The diesel-electric hybrids can operate in local service while the "clean diesels" using ultra-low-sulfur fuel can operate along express routes and hilly terrain. Articulated buses are available using the basic diesel propulsion. Moreover, the mixed fleet minimizes any risk relative to the diesel-electric hybrid technology, since hybrids would comprise a small part of the total fleet.

However, if the development of hybrid diesel-electric buses should progress more rapidly than our current evaluation indicates, then an even more aggressive position regarding hybrid buses might be pursued.

***Second choice* – Option A (or B), a mix of then-current state-of-the-art diesel buses, with the possibility of moving more aggressively into ultra-low-sulfur fuel buses that are fitted with advanced exhaust treatment systems.**

This option represents the best choice in the event that:

- diesel buses are able to meet the future EPA standards for emissions, and
- hybrid diesel-electric buses are not able to meet the current expectations regarding reliability, availability, and cost (for example, if the cost of diesel-electric hybrid buses does not fall below ~$350,000 by 2004).

Third choice – Option E, CNG buses, with an introductory year of diesel buses.

This option represents the best choice in the event that:

- diesel buses are not able to meet the future EPA standards for emissions, even using ultra-low-sulfur fuel, and
- hybrid diesel-electric buses are not able to meet the current expectations regarding reliability, availability, and cost.

In addition– Consider the purchase and testing of fuel cell-powered buses, at times and numbers that are yet to be determined.

Fuel cell-powered buses have considerable potential for operation as very quiet buses with very low on-board emissions. However, major developments are needed to achieve cost reduction, reliability, and range before these buses will be appropriate for wide-scale transit applications.

These buses should be considered for purchase after 2008 as this technology emerges. Viewed in this context, fuel cell-powered buses are an extension of hybrid technology.

Finally, as an overall recommendation, CONN-DOT and CTTRANSIT™ should continue their close monitoring of bus propulsion technologies. This recommendation recognizes the very rapid pace of change anticipated in transit bus propulsion, with improvements expected for many of the technologies that we have examined in this study.

IV. REFERENCES

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V. APPENDICES

APPENDIX A. LIST OF ORGANIZATIONS AND PERSONS CONTACTED DURING THIS STUDY

Connecticut Department of Transportation
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CTTRANSIT™
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Neoplan USA Corporation
- Tyce R. Light

New Flyer Industries
- Joel Abraman

Nova Bus Corporation
- Dennis C. Varden

Orion Bus Industries
- Joseph M. Bargar
- Bob Sonia

APPENDIX B. SUMMARY OF DYNAMOMETER TEST RESULTS

	EMISSION RATE (g/mile)						FUEL ECONOMY
	CO	NO_x	NMOC	PM	CO_2	CH_4	(mpg)
CBD Cycle							
Orion-LMCS VI Hybrid Diesel	0.1	19.2	0.08	0.12	2,262	0.0	4.3
Orion-LMCS VI Hybrid Diesel (no regen.)	0.04	22.0	0.12	0.24	2,625	0.0	3.7
Orion-LMCS VI Hybrid MossGas	0.1	18.5	0.03	0.02	2,218	0.0	4.2
Nova-Allison RTS Hybrid LS Diesel	0.4	27.7	bdl	bdl	2,472	0.0	3.9
Nova-Allison RTS Hybrid LS Diesel (no regen.)	1.0	32.1	0.03	0.07	3,010	0.0	3.1
NovaBUS RTS Diesel Series 50	3.0	30.1	0.14	0.24	2,779	0.0	3.5
NovaBUS RTS MossGas Series 50	1.0	32.2	0.05	0.09	2,816	0.0	3.3
Neoplan AN440T CNG L10 280G	0.6	25.0	0.60	0.02	2,392	14.6	3.1
New Flyer C40LF CNG Series 50G	12.7	14.9	3.15	0.02	2,343	17.4	3.1
Orion V CNG Series 50G	10.8	9.7	2.36	0.02	2,785	23.7	2.6
NY Bus Cycle							
Orion-LMCS VI hybrid Diesel	5.0	40.5	1.13	0.16	4,251	0.0	2.3
Orion-LMCS VI Hybrid Diesel (no regen.)	3.0	50.0	2.00	bdl	5,500	0.0	1.5
Orion-LMCS VI Hybrid MossGas	0.1	32.0	0.50	bdl	3,930	0.0	2.4
Nova-Allison RTS Hybrid LS Diesel	0.6	58.9	0.07	bdl	5,430	0.0	1.7
NovaBUS RTS Diesel Series 50	11.3	72.0	0.60	0.70	7,076	0.0	1.4
NovaBUS RTS MossGas Series 50	6.6	72.3	0.15	0.37	7,272	0.0	1.3
Neoplan AN440T CNG L10 280G	29.0	113.2	4.84	0.14	6,090	65.4	1.2
New Flyer C40LF CNG Series 50G	37.2	26.2	4.35	bdl	5,610	75.1	1.3
Orion V CNG Series 50G	31.7	15.3	6.64	0.11	6,535	66.7	1.1
Manhattan Cycle							
Orion-LMCS VI Hybrid Diesel	0.1	22.6	0.18	bdl	2,841	0.0	3.4
NovaBUS RTS Diesel Series 50	6.0	40.3	0.25	0.48	4,268	0.0	2.3
New Flyer C40LF CNG Series 50G	26.3	21.4	2.10	bdl	3,395	62.3	2.1

NOTE: bdl --Result was below the detection limit of the equipment.

Reports of the Academy

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

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

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- Urea-Formaldehyde Foam

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- The Opportunities and Limitations of Our Resource and the State of Our State in 2000 AD

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