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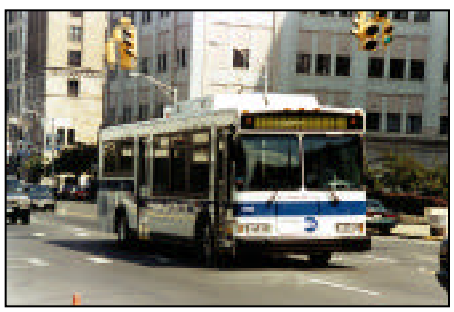
Analysis of Electric Drive Technologies For Transit Applications: Battery-Electric, Hybrid-Electric, and Fuel Cells



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13. ABSTRACT

This report provides an overview of the current status of electric drive technologies for transit applications, covering battery-electric, hybrid-electric and fuel cell buses. Based on input from the transit and electric drive industries, the analysis examines the state of electric drive technology for transit buses, including a list of current deployments; the benefits of major market penetration of electric drive buses to both transit and the broader community; the barriers that remain to achieving this goal; and potential steps the transit industry believes the Federal Transit Administration (FTA) could take to alleviate some of these barriers. The report focuses on hybrid-electric technology as the most commercially-viable technology for full-size transit buses today. There is a review of technical aspects of hybrid systems; emissions and fuel economy results to date; capital and operating costs; reliability, performance and durability issues; and regulatory status.

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The NAVC would like to thank the electric drive and transit industry representatives who agreed to be interviewed for this report. We would particularly like to thank the following individuals who provided additional information or expertise outside of the interview process: Kevin Chandler, Battelle/U.S. Department of Energy's Advanced Vehicle Testing Activity; Gary LaBouff, New York City Transit; Bart Mancini, BAE Systems; David Mazaika, ISE Corporation; David Mikoryak, GM Allison; Amy Miller, New Flyer of America, Inc.; Christopher Moog, New Jersey Transit; Michael Simon, ISE Corporation; Lurae Stuart, American Public Transportation Association; Stephen Warren, Connecticut Transit; and Thomas Webb, BAE Systems

About the NAVC

The Northeast Advanced Vehicle Consortium (NAVC) is a non-profit association of private and public sector firms that believe that advanced vehicle technologies, like fuel cells and hybrids, will play an important role in reducing the impact of the transportation sector on the environment and energy consumption. The NAVC strives to spur the successful implementation of these technologies through management of research and demonstration projects; development and dissemination of industry reports and other informational materials; and, outreach and advocacy efforts.

Originally formed by the Northeast States for Coordinated Air Use Management and the New England Governors' Conference, the NAVC was incorporated as a non-profit in Massachusetts in 1993. Today, the NAVC Board of Directors is appointed by the eight Northeast governors and the mayor of New York City.

The NAVC's three-part mission is to foster the development of transportation technologies that are clean, efficient, and sustainable; to help reduce the Northeast's air quality problems by promoting the use of clean-fueled vehicles; and to strengthen the region's economy through the creation of highly-skilled advanced transportation technology jobs.

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Acronyms

APTA	American Public Transportation Association
CARB	California Air Resources Board
CARTA	Chattanooga Area Regional Transportation Authority
CNG	Compressed Natural Gas
CO	Carbon Monoxide
DPF	Diesel Particulate Filter
EPA	United States Environmental Protection Agency
FTA	Federal Transit Administration
FTP	Federal Test Procedure
G/bhp-hr	Grams Per Brake Horsepower Hour
GVW	Gross Vehicle Weight
HC	Hydrocarbons
ICE	Internal Combustion Engine
LNG	Liquefied Natural Gas
Mi	Mile
MPG	Miles Per Gallon
MPH	Miles Per Hour
NiCd	Nickel Cadmium
NiMH	Nickel Metal Hydride
NMHC	Nonmethane Hydrocarbons
NOx	Nitrogen Oxides
NREL	National Renewable Energy Laboratory
PEM	Proton Exchange Membrane
PM	Particulate Matter
R&D	Research and Development
SAE	Society of Automotive Engineers
U.S.	United States

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Executive Summary

Transit agencies have become increasingly focused on making their bus fleets cleaner and more efficient by incorporating new clean propulsion technologies. This has led to increased interest in electric drive technologies as one option for cleaner, more efficient transit bus fleets. The primary electric drive options being explored are battery-electric, hybrid-electric and fuel cells. While there has been significant private sector investment in development of commercially viable electric drive options for transit, with significant progress being made, this effort still faces some barriers before electric drive buses can be truly competitive with conventional diesel buses.

This analysis examines the state of electric drive technology for transit buses; the benefits of major market penetration of electric drive buses to both transit and the broader community; and the barriers that remain to achieving this goal. The report strives to reflect the interests of the Federal Transit Administration (FTA) in supporting the U.S. transit community, promoting cleaner transit technologies, and ensuring high quality of transit services for the operators, riders and the community at large.

The analysis was developed based in part on research into the status of electric drive technologies in transit. More importantly, it was based on interviews with industry representatives from transit agencies, bus companies, hybrid system developers, fuel cell companies, engine manufacturers, and research and advocacy organizations. The results of the analysis are intended to reflect the interests and views of transit and electric drive stakeholders, not the views of FTA or of the report's author, the Northeast Advanced Vehicle Consortium.

Electric drive systems are appealing to transit because they offer the promise of reduced or even zero vehicle emissions; increased efficiency; enhanced performance; reduced fuel use; quiet operation; and, the potential for lower maintenance costs.

The results of research and the industry interviews indicate that pure battery buses have simply not reached viability for most transit service applications, and so are seen as a niche vehicle. Battery buses may still be purchased by users with a need for a zero-emission, no-noise bus; for example, for buses used indoors or in park areas. Fuel cells are seen as the long-term goal by many, with ICE-based hybrids offering a bridge to fuel cell buses, although there are some in the transit world who see fuel cells as unlikely to ever be commercially viable for transit. For those that see them as the long-term solution for vehicle propulsion, the timeframe for commercial products is seen as ten years at a minimum, with perhaps commercial fuel cells not being available for another 20 years.

Hybrid-electric buses have reached the commercial production stage. These are no longer primarily demonstration vehicles, although hybrid systems will continue to be developed and modified. There are approximately 700 hybrid buses in regular service in North America, with another 400 planned deliveries through 2006. Over 40 transit agencies in North America have hybrid buses in service, and transit agencies are announcing their intention to buy more. Hybrids have been shown to be technically viable for transit service. However, there are some major challenges that must be addressed, such as capital costs, battery life and longevity of components, and certification issues, for hybrid buses to be able to compete successfully with other bus technologies and reach greater levels of deployment throughout the U.S. transit system.

The report explores these issues and comes to the following major findings:

- Hybrid buses are an attractive option for transit agencies looking to deploy clean buses utilizing existing fueling infrastructure.
- The performance of electric drive technologies is attractive for transit agencies. These characteristics include improved acceleration, reduced noise and vibration, less brake wear and maintenance, and the possibility of limited zero emission operation. Drivers and passengers have responded favorably to hybrid buses.
- Fuel efficiency improvements are dependent on hybrid system architecture and bus duty cycle. To date, hybrid buses in service are showing approximately 10% to 50% better fuel economy.
- Testing results continue to indicate that hybrid-electric buses are comparable to or better than CNG and clean diesel buses in regulated emissions reductions, although some in-use testing results have not yet been released. As with fuel economy, emissions results will likely vary depending on the hybrid system configuration and the duty cycle.
- Hybrids offer clear benefits over CNG buses in the lack of major, expensive infrastructure modifications required. Hybrid buses do require some modifications, as well as training, relating to the high voltage system and some battery types.
- The capital cost premium for hybrid-electric buses remains high: approximately 60% to 80% higher than a comparable diesel bus. This results from the limited volume that is currently only driven by the transit market, as well as the high costs for energy storage.
- Energy storage systems continue to be the biggest technology concern for hybrids, as well as a cost concern. Battery life is unknown as this time because there is insufficient real world experience with hybrid buses. Battery replacement will be a significant operational cost.
- At current fuel prices, the initial price premium for hybrid buses will not be offset by the fuel savings over the life of the bus. Industry estimates are that hybrid bus prices must come down to around 30% over that of a comparable diesel bus for hybrid buses to compete on lifecycle costs; alternatively, diesel fuel prices would have to reach over $4.00/gallon.
- Current Federal heavy-duty vehicle emission certification procedures do not accurately reflect the emissions characteristics of a hybrid-electric bus. This may be a barrier to greater hybrid deployment as the stringent Environmental Protection Agency heavy-duty diesel bus engine emissions standards come into effect from 2007 to 2010. Hybrids will not be able to certify the entire hybrid system to the new standards, but instead will have to use a certified engine. This may be a barrier for hybrids in competing against diesel buses in the future.
- Current predictions for lifecycle costs and durability of hybrid systems and subsystems are based on limited real-world data, with the latest generation hybrid buses having been in revenue service for two years at most. This uncertainty may be a barrier for greater hybrid bus deployment. However, there is also uncertainty about the coming 2007 to 2010 diesel buses, which transit agencies must address in making procurement choices.

The transit agencies and electric drive stakeholders interviewed for this analysis were asked for their views on ways to address the remaining barriers or challenges to greater hybrid bus deployment. The following is a summary of industry opinions.

Addressing Cost Issues

- The development and adoption of a validated life cycle cost or cost of ownership method of procurement which could be applied to capital equipment procurements.

- Provide greater FTA share to cover the cost differential between hybrid and diesel buses.

- Support a revival of the Alternative Fuels Initiative program – or a comparable program – that will be targeted specifically to hybrid buses.

- Provide for capitalization of energy storage systems during the life of the vehicle or provide financial incentives to promote the use of more robust and durable energy storage systems.

- Create a depreciation "credit" for buses under 12 years old.

Addressing Technology Issues

- Provide continued funding support for testing and validation of improved energy storage in hybrid-electric bus applications.

- Provide funding for continued integration of, and improved options for, electrically-driven accessories and on-board diagnostics.

- Provide some additional maintenance and training resources during the initial deployment of hybrid technologies to preclude lack of knowledge from causing program failure.

- Promote technologies that reduce noise emissions from buses and vehicle systems.

Addressing Information-Related Issues

- Support a synthesis of the state of the technology that could provide a validated set of information that transit properties could use in decision-making procedures for capital equipment.

- Provide a resource for information from other sectors of government where similar research, testing, or deployment of technologies is occurring.

- Improve coordination of myriad government agency programs for hybrid buses.

Addressing Certification and Emissions Testing Issues

- Support a tailpipe emission certification process for heavy-duty vehicles.

- Support development of verification procedure for hybrid buses.

- Support revision of the SAE J2711 heavy-duty hybrid emissions testing standard.

- Develop a credit system for technologies that provide demonstrated improvements in fuel economy or lower overall energy usage.

Introduction: Objective and Approach

Over the last decade, transit agencies have become increasingly focused on making their bus fleets cleaner and more efficient by incorporating new clean propulsion technologies. Much of this effort has been driven by regulatory pressures. These include the stringent Environmental Protection Agency (EPA) heavy-duty diesel bus engine emissions standards that began in 2004 and those coming into effect from 2007 to 2010; the California Air Resources Board's (CARB) Public Transit Bus Fleet Rule and Emissions Standards for New Urban Buses; and requirements to meet Federal air quality attainment standards. Transit agencies are also sensitive to community pressures, and to the need to attract "customers" by offering the most appealing transit "product."

This drive has led to increased interest in electric propulsion technologies as one option for cleaner, more efficient transit bus fleets. Electric drive systems are appealing to transit because they offer the promise of reduced or even zero vehicle emissions; increased efficiency; enhanced performance; reduced fuel use; quiet operation, and, the potential for lower maintenance costs. This has led to greater private sector investment in development of commercially viable electric drive options for transit buses and heavy-duty vehicles, and significant progress has been made as a result. However, this effort still faces some significant barriers before electric drive buses can be truly competitive with conventional diesel buses. Therefore, this analysis will examine the state of electric drive technology for transit buses; the benefits of major market penetration of electric drive buses to both transit and the broader community; the barriers that remain to achieving this goal; and what industry believes would help alleviate some of these barriers.

What is Our Objective?

Present a picture of electric drive bus technology today, review how the industry got here, and explore where it may be heading.

To achieve this, the analysis gives an overview of the state of the following electric drive technologies for transit: battery-electric buses, hybrid-electric buses, and fuel cell buses. This report does not address electric trolleybuses, which draw electricity from overhead catenary lines; while these are an electric drive technology, they are a mature application with decades of proven transit service viability and an entirely different infrastructure system. This report is concerned with the development of "stand-alone" electric propulsion buses using on-board power. The report addresses adaptation of electric drive systems for all sizes of transit buses, but there is a greater emphasis on the full-size 40-foot bus as the most prevalent transit bus size. The analysis also briefly discusses the broader trend in transit toward adopting cleaner technologies, to help put the electric drive bus market into proper context.

Focus on the technology that is the most commercially viable for transit in the near-term: hybrid-electric buses.

Hybrid bus purchases have shown the most dramatic increase over the past five years, with several hundred buses placed into transit service since 2001 and more procurements in the works. Therefore, while hybrids are only part of the overall electric drive family, they are the technology that most transit agencies implementing electric drive buses in the near future will be deploying. This analysis reviews the state-of-the-art of hybrid buses today, focusing on technical issues like performance, reliability, and durability; capital and operating costs; training and safety; emissions and fuel economy; and regulatory status, especially emissions certification.

Describe the incentives spurring transit agency interest in, and procurement of, electric drive buses in general – and hybrid buses specifically.
The report outlines the key drivers for purchase of electric drive buses, as well as the benefits of these technologies to transit and the broader community.

Provide transit industry assessment of the barriers or challenges that remain on the pathway to widespread commercialization and deployment of electric drive buses.
This is the key goal of this analysis. The report will offer the views of transit and electric drive stakeholders – derived from transit industry interviews – about potential ways to overcome these challenges. The barriers that the analysis will focus on include technical, cost, regulatory, and institutional challenges.

How This Analysis Was Developed: Our Approach

The analysis was developed based on research into the status of electric drive technologies in transit and on input from a wide range of industry professionals with experience in electric drive buses. We received input from 28 industry representatives from transit agencies, bus companies, hybrid system developers, fuel cell companies, engine manufacturers, and research and advocacy organizations. Participating organizations were sent a survey, and then telephone interviews were conducted using the survey as a launching point for more in-depth discussion; a few participants chose to respond only in writing.

FTA provided feedback throughout the research and writing of this report. The report strives to reflect the interests of FTA in supporting the U.S. transit community, promoting cleaner transit technologies, and ensuring high quality of transit services for the operators, riders and the community at large.

The following is a list of individuals (with their affiliations noted) who participated in the survey:

Anthony Androsky, U.S. Fuel Cell Council
Thomas Balon, M.J. Bradley & Associates
Mark Brager, Orion Bus Industries
Bill Coryell, North American Bus Industries, Inc.
Jim Ditch, Long Beach Transit
Kevin Harris, Hydrogenics Corporation
Stephen Kukucha, Ballard Power Systems Inc.
Gary LaBouff, New York City Transit
Dana Lowell, M.J. Bradley & Associates
Brian Macleod, Gillig Corporation
Bart Mancini, BAE Systems
Dean McGrew, Azure Dynamics USA, Inc.
Michael Melaniphy, Motor Coach Industries Inc.
Marty Mellera, San Francisco Municipal Transportation Authority (San Francisco Muni)
Seyed Mirsajedin, Metropolitan Atlanta Rapid Transit Authority (MARTA)
David Mikoryak, GM Allison

> The questionnaire covered the following topics:
>
> - Procurement plans for electric drive buses
> - Drivers for buying electric drive buses
> - Barriers to greater deployment of hybrid buses, including cost, technical, regulatory challenges
> - Effect of 2007-2010 diesel engine emissions standards on the hybrid market
> - Useful life issues
> - Maintenance and training issues
>
> To see the questionnaire that was distributed to survey participants, go to Appendix A.

Christopher Moog, New Jersey Transit
John Nielsen, Southeastern Pennsylvania Transportation Authority (SEPTA)
Michael Powers, Caterpillar Inc.
Jack Requa, Washington Metropolitan Area Transit Authority (WMATA)
Michael Simon, ISE Corporation
Darryl Spencer, Dallas Area Rapid Transit (DART)
George Stites, King County Metro Transit
Lurae Stuart, American Public Transportation Association (APTA)
Stuart Thompson, AC Transit
Michael Tosca, UTC Fuel Cells
Stephen Warren, CT Transit
Thomas Webb, BAE Systems

Electric-Drive Technology Descriptions

For the purposes of this report, and to better understand the technologies discussed herein, a short description of battery-electric, hybrid-electric, and fuel cell technologies is provided below:

Battery-Electric: Consists of a relatively large electrochemical storage battery as the sole power source for the vehicle. It provides energy for propulsion through an electric traction motor(s) as well as power for all vehicle accessory systems. Battery-electric propulsion is a relatively mature technology; however, its applicability for mainstream transit operations is restricted due to limitations in electrochemical energy storage capacity versus energy required for a full day of operations. Battery-electric drive is also characterized by zero “point-of-source” (i.e., vehicle) regulated emissions.

Hybrid-Electric: Consists of a fuel-burning prime power source – generally an internal combustion engine (ICE) – coupled with an electrochemical or electrostatic energy storage device. These two power sources work in conjunction to provide energy for propulsion through an electric traction drive system. Power for all vehicle accessory systems can be provided electrically or mechanically from the ICE or combinations of both. Hybrid-electric propulsion is maturing rapidly and affords direct replacement capability in mainstream transit operations. This is because the combination of ICE and energy storage system are designed so that the batteries are never depleted, and range is limited only by on-board fuel. Hybrid-electric buses have comparable point-of-source regulated emissions as do CNG buses.

Fuel Cell: Consists of the fuel cell device itself which converts chemical energy into electric energy. It provides energy for propulsion through an electric traction motor(s), as well as power for all vehicle accessory systems. It can operate as a stand-alone prime power source or as the prime power source in a hybrid-electric drive system working in conjunction with an energy storage device. In transportation propulsion applications, fuel cells are still a developing technology. Fuel cells are also characterized by low to zero point-of-source regulated emissions, depending on the primary fuel stock (e.g., hydrogen, methane, alcohol, gasoline or diesel) on board the vehicle; hydrogen is the only fuel with zero point-of-source emissions.

Impetus for Transit Agency Interest in Electric Drive Buses

Before beginning the discussion of electric drive buses, it makes sense to clarify why transit agencies are interested in this technology. It is often noted why transit is an appealing application for new technologies: the public nature of transit operations, the centralized refueling and maintenance, the fixed nature of the driving routes, the use of professional drivers and maintenance staff, and the availability of government funding to support the higher cost of new technology. But why are transit operators interested in electric drive buses? It is important to address this question in order to determine potential steps that FTA may want to take to support the further commercialization and deployment of these technologies.

Therefore, as part of the survey for this report, interview subjects were asked about the primary drivers for placing electric drive buses in transit fleets. The responses reveal why transit operators find electric drive buses appealing as an alternative to conventional diesel buses, but also, and perhaps more importantly, why they may choose electric drive buses over the other clean alternatives to diesel buses – in particular, compressed natural gas (CNG) buses. In their responses, many agencies only addressed the appeal of hybrid buses, since hybrids are by far attracting the greatest interest from transit at this time; therefore, this section will sometimes speak only to the drivers for hybrid bus procurements.

Emissions reduction is the primary driver for transit operators who have adopted electric drive bus technology as an alternative to conventional diesel, as indeed is the case for adoption of other diesel alternatives like CNG, liquefied natural gas (LNG) or biodiesel. As already noted, the need to clean up their fleets has been driving transit operators to adopt diesel alternatives, and all transit operators interviewed for this analysis mentioned this as a major driver for purchasing electric drive generally, and hybrids specifically, over diesel buses.

Heavy-duty transit bus engines are regulated for emissions of particulate matter, carbon monoxide, nitrogen oxides and hydrocarbons. Particulate matter (PM) includes dust, dirt, soot, and smoke emitted by sources such as vehicle engines, factories, and power plants. PM can be a very localized problem, and is particularly likely to be a concern in urban areas with heavy-duty diesel vehicles in operation. Exposure to PM can result in breathing and respiratory symptoms, alterations in the body's defense systems against foreign materials, and damage to lung tissue. Carbon monoxide (CO) is also a localized emission concern, with the impact of vehicle-related emissions typically occurring in low-lying areas such as urban canyons. When CO gets into the body, it combines with chemicals in the blood and impairs the ability of blood to carry oxygen to cells, tissues and organs. EPA and CARB regulate the vehicle emissions of nitrogen oxides (NOx) and hydrocarbons (HCs) in an effort to control ozone. Ozone is the major component of smog and is formed through complex chemical reactions between emissions of HCs and NOx. These reactions are stimulated by sunlight and temperature, so peak ozone levels occur typically during the warm weather seasons. High concentrations of ozone at ground level are a major health and environmental concern.

The transit agencies we interviewed confirmed that this interest in cleaner fleets is driven primarily by regulatory and political pressures. This pressure is most marked in California, where transit agencies are required to adopt clean alternatives to conventional diesel buses under CARB's Public Transit Bus Fleet Rule. Transit agencies that have opted for the diesel path are allowed to procure diesel-hybrid buses, while gasoline-hybrids are permitted under both the diesel path and the alternative fuel path. In addition, the CARB Public Transit Bus Fleet Rule requires all large bus fleets to begin purchasing "zero emission buses," which will primarily mean fuel cell buses in the 2008 to 2010 timeframe. There are some agencies – like AC Transit, SunLine Transit, and Santa Clara Valley Transportation Authority with San Mateo Transit – that are already demonstrating fuel cell buses (required by this Rule for large transit fleets on the diesel path), while others, like San Francisco Muni, have made long-term commitments to adopting fuel cell buses as they become commercially viable.

Outside of California, where transit buses are subject to EPA bus emissions standards, the drive to reduce transit fleet emissions – beyond levels required by EPA's transit bus engine standards – can have varied sources. Many transit operators who have opted to adopt electric drive buses are located in areas that are in non-attainment with Federal air quality standards. These agencies are seeking to reduce emissions as part of a coordinated effort to bring their region into compliance. Other transit agencies are facing local political and community pressure to clean up their fleets.

Battery-electric and fuel cell buses offer zero emissions from the vehicle, while hybrid-electric buses lower levels of all regulated emissions, with significant reductions in CO and NOx over current diesel buses and PM levels comparable to clean diesel with particulate filters. However, there are other clean alternatives to diesel buses that are available to transit agencies – CNG buses being the most popular. Many respondents were blunt in their assessment that the current interest in hybrid buses (as opposed to battery-electric or fuel cell buses) arises from the desire to find a clean alternative to CNG. CNG buses have enjoyed a significant increase in their share of the U.S. transit bus fleet over the last two decades; the latest American Public Transportation Association (APTA) Fact Book shows CNG buses comprising 11% of the total bus fleet (as of the end of 2004). However, some transit agencies have been reluctant to deploy CNG buses because of the expensive infrastructure overhaul required to fuel, service and store the buses. Hybrid-electric buses, which at this time are primarily diesel fueled, offer the possibility of reduced emissions without this significant infrastructure expense. In addition, CNG buses were the subject of a major push by environmental advocacy groups over the past two decades; this advocacy was successful, as many transit agencies purchased CNG buses to address community concerns about diesel bus emissions. But until recently, CNG was the only commercially viable clean fuel alternative to diesel. Now, many transit agencies are interested in hybrid buses because they are a strong competitor to CNG buses in terms of emissions reductions and viability in real-world operations.

Beyond the desire for a cleaner fleet, another major driver for electric drive buses is reduced fuel consumption. After labor costs, fuel cost is the second largest operating expense for transit agencies. Battery-electric and fuel cell buses are, of course, petroleum-free options (in terms of the onboard fuel), while hybrid buses are demonstrating fuel economy increases of 10% at a minimum and as much as 48% over a conventional diesel bus; CNG buses' fuel economy is lower than that of diesel and hybrid buses.

Transit operators also noted several characteristics of an electrically driven bus propulsion system over an internal combustion or CNG system that are positives for the drivers, maintenance staff, riders and the wider community. Transit operators cited these attributes of electric drive systems that make them appealing as a clean alternative to diesel buses:

- Reduced noise level from the bus

- Reduced brake wear-and-tear, resulting in extended brake life
- Potential for reduced maintenance (fewer oil changes, less engine wear-and-tear)
- Better acceleration from a stop and potential for better hill-climbing ability
- Appeal to passengers (for "clean" image and smoother driving)

The reduced noise benefit was cited as especially appealing, because communities are starting to focus more on the noise pollution from bus fleets now that the buses' emissions are cleaner. Some transit agencies think that noise pollution is the next frontier in community activism affecting transit operators, and that electric drive buses will help alleviate this as an issue.

Finally, some industry representatives noted that current hype surrounding hybrid technology may be one of the factors driving transit agency interest in hybrid buses right now. Certainly there is a buzz about hybrid technology, due in part to the rise in the number of hybrid cars on the road in the U.S. In addition, widely publicized results from the two biggest hybrid bus deployments in the U.S. – King County in Seattle and New York City Transit – have helped raise interest among transit operators. For now, though, this has led primarily to transit agencies undertaking demonstrations for small test fleets of hybrid buses, typically one to five buses at a time. The real test for hybrid buses will be whether they make the transition from this early level of interest to a widespread, mainstream transit option. Ultimately, true commercial viability will be contingent upon adoption of hybrid technology by commercial and military truck fleets. Only then will there be sufficient vehicle volumes to become more than a niche product.

Status of Electric-Drive Technologies in Transit Applications

This section will provide a general overview of electric drive technology being incorporated into transit bus applications. As already noted, this report only examines electric drive buses with an on-board power source, not electric trolleybuses, which draw electricity from overhead catenary lines. The three types of "stand-alone" electric drive systems currently being demonstrated or deployed in transit applications are battery-electric, hybrid-electric, and fuel cell buses.

This section will give a brief overview of each type of technology, including infrastructure needs; describe advances that have been made over the last decade toward making these applications commercially viable; discuss current understandings of capital, maintenance and operating costs; review the status of current and planned deployments (as of July 2005); and, highlight the main barriers to greater deployment. This is not intended as an in-depth technical review, as the purpose of this report is to give a broad view of the status of electric drive in transit applications and challenges to more widespread commercial penetration. Detailed technical information on electric drive technologies for transit can be found in the sources listed in the *Bibliography and Further Reading* section. These references were also used as sources for some of the technical information in this section and the *Focus on Hybrid-Electric Transit Buses* section.

Overview

Although transit agencies have been using electric power in their transit systems since the late 1800s, with the introduction of electric trolleys, "stand-alone" electric-powered buses have only been practically viable for transit operations since the last decade. In some ways, the development of electric drive buses tracks that of electric passenger cars, which also began receiving greater attention beginning in the 1990s. Throughout that decade, much of the research and development activity for electric propulsion buses focused on pure battery-powered systems, as was also the case with electric passenger cars. Beginning in the late 1990s, however, hybrid systems began to attract more development attention, for both light-duty and heavy-duty applications.

Much of this shift was due to the limitations of currently available battery technology. The primary technological – and cost – factor driving development of electric propulsion systems has been the battery. The search for a battery technology that will provide sufficient range (300 to 400 miles) for typical transit operations, with a reasonable weight and size, and at a commercially-viable cost, has really directed the commercial fortunes of electric drive buses. In the late 1990s, hybrid systems using diesel or gasoline engines in combination with an electric motor began to be seen as a solution to range and performance limitations of commercially viable battery technology for all-battery transit applications. Today's diesel and gasoline hybrid buses allow for some of the benefits of electric drive – greater efficiency, lower emissions, reduced noise – while maintaining the performance standards and vehicle utility of, and utilizing the existing refueling infrastructure for, diesel buses. Efforts to develop better energy storage options are still being explored by hybrid system integrators. Ultracapacitors, which store energy electrostatically by polarizing an electrolytic solution, are an emerging technology that is being used on roughly 80 hybrid buses in service today. Other advanced battery chemistries such as lithium, as well as other energy storage systems like flywheels and hydraulic systems, are also in a pre-commercial stage but are attracting continued research and development (R&D) dollars by companies eager to improve weight, range and cost characteristics of today's commercial battery technologies.

The common element on this technology pathway is the electric drive train, and this technological focus continues to the next phase of electric power sources: the fuel cell. Propulsion systems based on fuel cell prime power units generate electricity from hydrogen to power an electric motor. There has been significant attention paid to developing fuel cells for transportation, with transit buses being used as a test bed to advance the technology toward commercialization.

Battery-Electric Buses

Overview: Battery-electric buses are often referred to as "pure" electric buses because the propulsion system is powered only by the electric energy stored in the battery. The battery pack is either recharged daily or "swapped out" when the batteries are depleted. Battery-electric propulsion systems are primarily targeted to smaller transit buses, such as those used for shuttle service or other vehicle routes that are short and low speed. This is due to the limited range and power of current commercial battery technologies. Because of the potential benefits of using zero emission buses in public fleets, there has been much R&D funding devoted to improving the battery technology over the last decade. In spite of this, battery-powered buses have not been able to achieve sufficient range at a commercially competitive cost. As a result, today there are only a handful of manufacturers offering battery-electric buses, primarily in the medium-duty shuttle bus market. Today there are approximately 90 to 120 battery-electric buses in transit operations. This deployment level is actually down somewhat from the mid-1990s, reflecting the drop-off in transit operator interest due to the failure of industry to achieve a major battery breakthrough. For those knowledgeable about the light-duty electric vehicle market, this is a familiar trend.

Primer on Battery-Electric Technology for Transit Applications: Before discussing the current state of battery-electric buses and barriers to further commercial deployment, it is important to have a basic understanding of the technology and how it works. The battery-electric technology review will, of course, also be applicable to an understanding of how hybrid-electric and fuel cell systems operate. (Note: This report is not intended to provide an in-depth technical discussion; for more detail on battery-electric drive systems, see the *Further Reading* section.)

The drive system for a battery-electric bus consists of an electric motor, a battery pack to provide energy storage, and a control system that governs the vehicle operation. Electric motors offer greater efficiency and less noise than internal combustion engines (ICE). They provide their highest torque at low speeds, which results in better acceleration from a stop. Electric motors also increase energy efficiency by enabling regenerative braking: when the vehicle decelerates, the motor reverses field, becoming an electricity generator that can recharge the battery pack during braking events. In a conventional internal combustion engine system, braking energy is lost, as there is no mechanism to recover it. The ability to recover this energy is one of the key benefits of electric drive systems, adding to the overall higher efficiency of electric drive. The electric drive control system is quite complex, as it must receive input from the operation of the vehicle, and direct the response of the electric drive system. It is now common for conventional vehicles to have some level of complex electrical systems and controls, so this not a completely unfamiliar element for transit operators.

Battery-electric buses must be recharged daily – or have the battery pack swapped out for a new one, an unlikely solution for most transit operations – so transit agencies must purchase expensive charging equipment to recharge the fleet. Recharging time varies, dependent on the battery type, capacity and voltage/current output of the charger. Most electric buses will be able to receive a full recharge in six hours, although "fast-charger" systems can reduce this to about two to three hours for certain battery types (see battery discussion below). Fast charger systems are a more expensive piece of equipment, however. One strategy for addressing the problem of insufficient range is opportunity charging, where a fleet will recharge the bus during its daily service, at charging stations placed at key spots on the bus fleets' routes. This adds significant infrastructure costs, and presents challenges to delivering reliable, timely transit service which depends on adhering to tight schedules.

As with all electric propulsion vehicles, support and training in understanding high voltage vehicle systems safety is required. Mechanic training in how to service and troubleshoot electric propulsion components is required. These can be concerns for transit agencies considering adopting electric bus technologies, as will be discussed in greater detail in the *Barriers and Challenges to Widespread Deployment of Hybrid-Electric Transit Buses* section. Transit agencies that operate rail systems are familiar with the requirements of operating and maintaining high voltage electrical propulsion systems, although there may not be much overlap between the rail and bus staff.

Most battery-electric buses today are equipped with lead acid or nickel cadmium batteries, the most commercial of today's battery technologies. At this time, neither of these battery types have sufficient energy density (energy per weight) to allow for a full load of passengers and sufficient range, 300 to 400 miles, at the same time, if the bus is powered exclusively by batteries. Consequently, powering a full-size bus would require a battery pack that is unacceptably large and heavy, as well as too costly to make a battery-electric bus commercially competitive.

Lead acid batteries require the longer recharging time of about six hours, while nickel-cadmium batteries can take a faster charge. Nickel cadmium batteries have higher upfront cost than lead acid, but are smaller and lighter than lead acid batteries, and offer maintenance and operations benefits over lead acid batteries in daily transit service.

In an effort to address the battery issue, several advanced battery options have been explored for battery-only bus applications, including nickel metal hydride, sodium nickel chloride, lithium, sodium-sulfur, and zinc-air. To date, none of these has proven to be viable options for battery-only buses because they are too costly or have not been proven in long-term transit operations. Ultracapacitors, another advanced storage option, cannot be used as the sole energy storage device in a pure electric bus; they are used only in hybrid configurations.

By contrast, lead acid and nickel metal hydride batteries are the primary energy storage options used in today's commercial hybrid bus products. In a hybrid configuration, these batteries are able to meet the performance needs of transit agencies, although they still have some reliability, durability and cost limitations that are causing hybrid system developers to invest R&D dollars in other energy storage options.

Benefits: The primary benefit of battery-electric buses is the absence of vehicle tailpipe emissions. The impact on the region's emissions is dependent on the power generation process for that region. Recharging the vehicles during off-peak hours eliminates any issue of capacity for electrical generation. There have been a variety of studies attempting to compare the well-to-wheels emissions of battery-electric vehicles to those of conventional ICE vehicles. Clearly, the biggest factor is how clean the region's electricity supply is. In any case, it is the "zero in-use emissions" aspect of these vehicles which makes them appealing in certain environmentally sensitive areas, like downtown pedestrian zones and national parks.

The other major benefit is the lack of noise, due to the absence of an engine and mechanical transmission system. Again, for certain highly sensitive environments that place a premium on noiseless, low-impact vehicle operation, battery buses will hold an appeal, as long as these transit areas have short, undemanding routes. Another benefit of electric buses can be the positive reaction from the public and riders. Battery-electric buses are still a novelty, and have proven appealing in communities where they have been deployed for their smooth, quiet ride and lack of tailpipe fumes. Miami Beach, Florida has had a highly successful downtown electric shuttle program; deployment of the all-electric buses led to a major increase in ridership. The Santa Barbara Metropolitan Transit District (MTD) in California also found that its riders preferred the battery buses over diesel buses. Santa Barbara MTD deployed all-battery shuttle buses in low mileage routes in their downtown shopping district, where the quiet and zero emission features were highly desirable, leading to an increase in ridership.

Capital, Maintenance, Operations Costs: Procurement costs for battery-electric buses are significantly higher, due to the high cost of batteries and the lack of economies-of-scale for production. At this time, battery-electric buses are a "boutique" transit option, with very small numbers of orders. For example, Santa Barbara MTD, which has been one of the leaders in adopting battery-electric buses, was forced to rethink plans to purchase more 22-foot electric shuttle buses in 2003 when it received only one bid of $580,000 per bus.

Battery replacement is another major capital cost associated with this technology, which can add several thousands of dollars to the lifetime cost of the buses. Transit operators must purchase electric charging equipment to recharge the fleet, an added operational cost that offsets some of the potential savings that result from eliminating diesel or gasoline fuel consumption. Any battery-electric bus fleets' fueling costs will depend on the region's electric rates. Maintenance and operations costs can also be reduced since electric drive systems have fewer parts than an ICE system.

Current Deployments: Because of the weight and range issues, the vast majority of battery-electric buses in service today are 22-foot shuttle buses. The biggest fleets are in Santa Barbara, California and Chattanooga, Tennessee which both became living laboratories for battery bus technology. The Chattanooga Area Regional Transportation Authority (CARTA) made a commitment to an all-electric bus fleet in the early 1990s, and continues to run a fleet of 12 buses for their downtown circulator. For this type of service – limited mileage, urban operations – the battery buses are a good fit, and the all-electric shuttles have proven popular. CARTA is operating buses that are between five to eight years old, and expects to get an additional three to five years from them, at which time CARTA plans to purchase all-battery replacements. As noted above, Miami Beach has had a successful downtown electric shuttle program, but the future of this fleet is uncertain since the shuttle service is being taken over by Miami Dade

Transit in September 2005. Santa Barbara MTD continues to operate a fleet of 20 battery buses. Although they had to postpone their 2003 plans to procure more battery-electrics, they are planning to issue a Request for Proposals for 13 22-foot all-electric shuttle buses in September, 2005. (Santa Barbara MTD is also participating in pooled procurement of full-size hybrid-electric buses.)

Overall, in spite of some success stories, battery buses' share of the market has leveled off, with few new purchases being made. Deployments are down from the 1990s, as older buses have gone out of service and not been replaced by new battery bus purchases. The two major factors that have kept battery buses from increasing their market share are the battery limitations and the cost. In addition, because battery buses are built as a niche vehicle, there are few companies in this market, and one of the biggest electric bus companies from the 1990s, Advanced Vehicle Systems Inc., has gone out of business. This limits options for fleets interested in battery buses.

There is one 40-foot pure electric bus being developed, using a pre-commercial battery technology. Electric Fuel Corporation is developing and demonstrating a 40-foot electric bus powered by a zinc air cell, along with an ultracapacitor. The zinc air energy device, often described as a battery, converts zinc to zinc oxide in a process that provides energy to the bus. The bus is not recharged; instead, the zinc oxide cartridges are swapped out for new ones. This bus has shown a range of over 100 miles in testing and has been demonstrated in Las Vegas, Nevada. However, this technology is in the development phase, and several major hurdles must be overcome before it can be adopted for transit fleet use, including available refueling infrastructure.

Conclusion: The majority view of the industry representatives interviewed for this report is that battery technology simply has not advanced to the point where pure battery buses are viable for most transit operations. For the foreseeable future, barring any major battery technology breakthrough, these buses will be niche vehicles, viable for shuttle bus operations in certain environments where zero emissions or no noise are preeminent concerns, and where the driving conditions and vehicle accessory load do not overly tax the battery packs. In these circumstances, all-battery buses can be a desirable choice, as they do hold appeal for riders and help transit operators act as a "good neighbor."

Active Battery-Electric Bus Deployments in the U.S. (as of July 2005)
Note: This list only includes fleets of five or more that could be confirmed.

Site	Number	Size	Bus Company
Anaheim, CA	10	22'	Ebus
Atlanta, GA (Emory Univ.)	5	22'	Ebus
Chattanooga, TN	12	22'	Advanced Vehicle Systems (AVS)
Colorado Springs, CO	5	22'	Ebus
Hampton, VA	8	22'	AVS
Los Angeles, CA	18	22'	Ebus
Miami Beach (status uncertain after Sept. 2005)	10	22'	AVS
Mobile, AL	4	22'	Ebus
New Haven, CT	4	22'	Ebus
Santa Barbara, CA	20 total		
	1	22'	APS
	3	22'	BMI
	10	22'	Ebus
	6	22'	Specialty Vehicle Manufacturing Corp.

Hybrid-Electric Buses

Overview: A hybrid-electric vehicle is one that combines an electric propulsion system with another power plant such as a conventional internal combustion engine (diesel, gasoline, propane, or natural gas), a turbine, or a fuel cell stack. In the case of hybrid-electric buses, the majority in service today use a diesel or gasoline engine with an electric motor and batteries, while a smaller number of hybrid buses in service use an ultracapacitor for energy storage. This combined system of an ICE engine, electric motor and energy storage device gives a transit operator the benefits of an electric drive system – better acceleration from a stop, quieter operation, greater energy efficiency – without the negatives of a pure battery-electric bus, like reduced range and reduced hill-climbing power. In addition, commercially-available hybrid buses today do not require recharging: the batteries are continuously recharged during driving, as with commercial hybrid passenger cars like the Toyota Prius and Honda Civic Hybrid (although there are some efforts to develop a plug-in hybrid bus for transit agencies that may want a battery dominant bus). Thus, while transit operators will not receive the zero "point-of-source" emission benefit of a pure battery-electric bus, hybrids will lower emissions and fuel use, while providing the kind of performance that transit operations require. Because of these benefits and vehicle utility, hybrid bus sales in North America have increased dramatically over the past three years. Today there are approximately 700 in service and another 400 due for delivery in late 2005 and 2006, with active Requests for Proposals and options for several hundred more.

Primer on Hybrid-Electric Technology for Transit Applications: As noted above, hybrid-electric buses combine two energy sources, one an electrochemical or electrostatic storage device and the other a fuel-burning prime power source. The prime power source could be any device which converts chemical fuel to mechanical energy, and is most often a diesel or gasoline engine, as this allows the buses to use the same fueling, maintenance and storage infrastructure as conventional ICE buses. Thus, today's hybrid-electric buses combine the elements of the battery bus described earlier – the electric motor, controller, battery packs – with an ICE which is most typically a diesel engine, and less frequently a gasoline engine, coupled to an electric generator. In addition, a number of hybrid buses in service today replace the battery packs with an ultracapacitor, an advanced energy storage option.

The hybrid system allows the engine to operate in a more efficient mode, by "sharing" the energy and power demands of vehicle operations between the batteries and engine. The batteries can provide the traction motor with extra power as needed for acceleration or steep grades; this allows the engine to operate in a more "steady-state" mode, increasing the efficiency of in-use engine operation. The electric motor and energy storage also allows for energy recovery through regenerative braking, as described in the battery-electric bus section. Regenerative braking allows the propulsion system to apply a retarding load on the drive axle during braking, thus converting the vehicle's kinetic energy into electrical energy. The vehicle stores that energy onboard, to be used to drive the wheels at another time.

The overall efficiency of a hybrid-electric system depends on which system elements are selected, how these various systems are integrated, and the electronic control strategy. Currently, there are two major configuration strategies for hybrid-electric vehicle systems: series or parallel.

> *Series:* In a series hybrid, the engine is completely mechanically decoupled from the drive wheels. All of the energy produced from the engine is converted

to electric power by the generator, which powers one or more electric traction motors as well as recharging the energy storage device that provides supplemental power. The electric motor system – by itself – provides torque to turn the wheels of the vehicle. Because the combustion engine is not directly connected to the wheels, it can operate at a more optimum rate, and can be switched off for temporary all-electric, zero-emission operation.

Parallel: In a parallel hybrid, both the combustion engine and the electric motor have direct, independent connections to the transmission. Either power source – or both of them together – can be used to turn the vehicle's wheels. These vehicles are often designed so that the combustion engine provides power at high, constant speeds; the electric motor provides power during stops and at low speeds; and both power sources work together during accelerations.

This report will not discuss in depth the various ways of configuring a hybrid-electric drive system. The main point is to keep in mind that hybrid systems, by definition, can be configured in a variety of ways, and operational characteristics will vary accordingly. Transit agencies will want to be aware of the technical characteristics of competing hybrid systems, and ensure that they specify a hybrid system that will meet their in-service needs. Some of the trade-offs that can be made in designing the system are power, efficiency, battery life, and all-electric operation. In addition, manufacturers are still fine-tuning their hybrid systems, making adjustments as hybrid buses gain more real-world service.

As noted, today's commercial hybrid bus products generate all the electricity they need on-board and do not need to be recharged. The battery pack is simply recharged during the course of normal driving (with some reconditioning necessary for certain battery types, as will be discussed in the *Focus on Hybrid-Electric Transit Buses* section). This allows the bus to avoid the range problems of pure battery buses.

It is possible for a hybrid bus to be designed to be "charge depleting" which would mean that the vehicle batteries (or energy storage device) would need to recharged on a regular basis. The all-electric range of a so-called "plug-in" hybrid-electric vehicle would be longer than that of non-plug-in hybrid, but the bus would also run with the ICE engine, giving it a better range than an battery-only bus. For the most part, transit agencies want to use their existing diesel or gasoline refueling infrastructure, and are not exploring plug-in hybrids. There is a demonstration program underway by the Electric Power Research Institute involving a DaimlerChrysler Sprinter van; the expectation is that the plug-in hybrid system being developed for the Sprinter is applicable to medium-duty shuttles. Project partners are aiming to produce a fleet of 30 of these pre-commercial vehicles for testing and evaluations across the U.S. over the next few years. For agencies that require or desire a significant all-electric range, plug-in hybrids, if proven commercially viable, will be a good option.

As discussed in the previous section, most hybrid transit buses in use today are equipped with either lead-acid or nickel metal hydride batteries, and these will likely continue to be the primary options for commercial hybrid buses over the next few years. This is because both have been proven in real world service, in the two biggest hybrid fleets to date: the 225 buses delivered to date in New York City Transit are equipped with lead acid, while the 214 bus fleet in Seattle use nickel metal hydride. However, these batteries still have some reliability, durability, weight and cost limitations that are causing hybrid system developers to invest R&D dollars in other energy storage options. The most developed option to date is the ultracapacitor, which is being used in over 80 buses integrated by ISE Corporation. The ultracapacitor offers the promise of high power rates, light weight and long life at a reasonable cost. Ultracapacitors have had trouble sustaining charge during hill climbing, limiting their applicability for transit agencies with steep grades in their routes.

Benefits: The appeal of a hybrid-electric system is that the electric drive can improve drive system efficiency, reduce emissions, and reduce energy consumption. This results from the optimized integration of the system, to best capitalize on the efficiency of the electric drive system. This efficiency improvement is achieved by two primary means: the ability to operate the engine in a more efficient mode, and the recovery of regenerative braking energy. Regenerative braking can also save wear-and-tear on the brakes. In addition, hybrid buses, while not virtually noise-free like battery buses, are quieter than conventional diesel buses since the buses typically use a smaller diesel engine and operate the engine in a more steady-state mode, reducing the noise associated with acceleration of typical heavy-duty diesel engines. In addition, depending on the hybrid system configuration, some buses can operate in an electric-only mode in low speed operations. Hybrid-electric buses are also able to utilize electrically driven accessories, thereby further increasing the overall bus efficiency.

Another significant benefit of hybrids is the ability for transit agencies to use their existing diesel or gasoline fueling infrastructure. This reduces the cost to the transit agency for deploying hybrids, and, importantly, removes what can be a major hurdle for transit agencies interested in exploring a cleaner technology option without making a major financial commitment, as is required when adopting CNG buses. This has resulted in many transit operators across the country placing five or fewer hybrid buses in their fleets, to evaluate them for applicability in their operations before making future procurement decisions.

Capital, Maintenance, Operations Costs: Currently, hybrid buses carry a significant price premium over conventional diesel buses. It is difficult to predict the price differential since hybrid bus prices will vary from one procurement to the next, depending on the order number and the specifications. Further complicating cost comparisons is the fact that, while diesel buses are a very mature technology with well understood costs, diesel bus prices are currently somewhat of a moving target, as emissions standards for diesel bus engines tightened significantly in 2004, and will continue to do so when the new regulations come into effect from 2007 to 2010. Engine manufacturers and bus companies will have to employ more advanced engine control systems and aftertreatment devices, which will likely increase the price of diesel buses. Nevertheless, we can estimate that a model year 2006 40-foot diesel bus costs approximately $280,000 to $300,000. A 40-foot hybrid bus today typically costs between $450,000 and $530,000. On average, hybrid buses being sold today are approximately 60% to 80% more expensive than a comparable diesel bus.

The other major cost associated with hybrid buses is battery replacement, as batteries today are not expected to last the 12-year life of a transit bus. The primary battery selections in use today are lead acid and nickel metal hydride. These battery types offer trade-offs in terms of weight, cost, performance and durability. Lead-acid is the most mature technology and can be purchased off the shelf. They are cheaper than nickel metal hydride batteries, but also have a shorter estimated life of approximately three years. They also require periodic reconditioning of the battery; nickel metal hydride batteries (NiMH) do not. NiMH batteries are lighter than lead acid. They cost more upfront, but are predicted to last longer, from five to seven years. The question of battery costs will be discussed in the *Hybrid-Electric Bus* section.

One of the biggest cost savings associated with hybrids, of course, is the reduction of fuel consumption compared to conventional diesel buses. This differential may become more pronounced as diesel buses incorporate more advanced emissions control systems that may reduce diesel buses' fuel economy. Hybrid buses may also offer some other operational cost savings, which will be discussed in the next section.

Current Deployments: Five years ago, New York City Transit was testing 10 hybrid buses; today, there are approximately 700 hybrid buses in regular service in North America, with another 400 planned deliveries through 2006. Over 40 transit agencies in North America have hybrid buses in service, and transit agencies are announcing their intention to buy more. New York City Transit recently accepted bids for a new order of 364 hybrids, with an option for an additional 525. The Washington Metropolitan Area Transit Authority (WMATA) in the District of Columbia has announced plans to purchase 100 hybrids over the next three years, in the first stages of a long-term plan to deploy hybrids; they will issue a request for bids by the end of 2005. For both agencies these hybrid bus procurements are part of a strategy to shift from CNG buses to hybrids (and clean diesel) to replace old diesel buses with cleaner options. Both agencies face community pressure to clean up their fleets, and have CNG buses in service, but decided to purchase hybrids in order to avoid the CNG infrastructure costs.

By far, the majority of hybrids delivered and on order are 40-foot buses, but there are also deployments of 22-foot shuttle and 60-foot articulated buses. Most are diesel-hybrid, but there are a mix of gasoline-hybrids, particularly in California where gasoline-hybrids can be used to comply with both of the CARB Public Transit Fleet Rule bus "pathways."

The biggest fleets are in New York City, which has 225 in service and another 100 due for delivery by the end of 2005, and King County in Seattle, which has 214 (and an additional 22 from the same order in service at Sound Transit). Most other deployments are fairly small, many under ten. Many of these transit agencies are evaluating the technology in their fleets before committing to major hybrid purchases. In addition, some of these transit agencies are looking to the big fleets like Seattle and New York City to work out any issues with the latest generation of hybrid buses, benefiting from their experience when the hybrid bus manufacturers upgrade and improve their products.

There are currently three major hybrid system companies in the full-size transit bus market: GM Allison Transmission, British Aerospace Engineering (BAE) Systems, and ISE Corporation. These three companies' products comprise the vast majority of 40-foot hybrid buses on the road today, and all are offering hybrid buses as commercial products, not as demonstration vehicles. The other major hybrid bus provider, Ebus, produces 22-foot shuttle hybrid buses.

The following chart is intended only as a snapshot of each hybrid system manufacturer producing full-size commercial products for transit today. These companies may offer new or upgraded products in the future, may partner with other bus companies, and may offer hybrid drive for other bus sizes.

Major Hybrid System Manufacturers for Full-Size Transit Buses

BAE Systems:
BAE Systems uses a series hybrid system configuration, and its buses are equipped with lead acid battery packs and diesel engines. To date, BAE has partnered primarily with Orion Bus Industries. BAE and Orion have produced several generations of hybrid buses, beginning with the pilot fleet of ten buses from 1998. After extensive in-service testing, New York City Transit placed an order for 325 additional hybrid buses, to be delivered in two separate orders; to date, 225 have been delivered. BAE recently announced major new orders from Toronto Transit and San Francisco Muni.

40-Foot BAE Systems-Orion Diesel Hybrid Bus in San Francisco
Courtesy BAE Systems

GM Allison:
GM Allison produces hybrid systems of the parallel configuration. Their hybrids today are equipped with nickel metal hydride batteries and diesel engines. They have primarily partnered with New Flyer and Gillig in developing hybrid bus products. With New Flyer, they have developed a 40-foot hybrid bus and a 60-foot articulated hybrid (as is used in Seattle); they have also produced 40-foot buses with Gillig. They also worked with Motor Coach Industries (MCI) to develop a hybridized over-the-road coach for New Jersey Transit. GM Allison has over 350 buses in service today, at over 28 locations in North America.

40-Foot New Flyer Bus Equipped With GM Allison Diesel Hybrid System
Courtesy New Flyer of America, Inc.

ISE Corporation
ISE Corporation is a small company based in California that integrates both hybrid and fuel cell drive systems, as well as hydrogen ICE systems. ISE's hybrid drive is a series configuration. ISE has produced hybrid buses with gasoline engines in addition to diesel-based buses, and their buses have incorporated a variety of energy storage options; most now use ultracapacitors. They have partnered with several bus companies, including NovaBus, New Flyer and Gillig. They have a total of 85 buses in service, with several dozen more on order.

40-Foot ISE-New Flyer Gasoline Hybrid Bus in Long Beach
Courtesy ISE Corporation

Active Deployments or Confirmed Pending Deliveries of Hybrid-Electric Buses in the U.S. and Canada (as of July 2005)

Location	Ordered	Delivered or date due	Size	Bus Company	Battery	Fuel
GM Allison Transmission						
Albuquerque, NM	N/A	12	60'	New Flyer	NiMH	Diesel
Austin, TX	N/A	2	40'	New Flyer	NiMH	Diesel
Baltimore, MD	10	2006	40'	New Flyer	NiMH	Diesel
Charlotte, NC	N/A	2	40'	Gillig	NiMH	Diesel
Chicago, IL	10	2006	40'	New Flyer	NiMH	Diesel
Cleveland, OH	21	2006	60'	New Flyer	NiMH	Diesel
Edmonton, AB	2	2006	40'	New Flyer	NiMH	Diesel
Eugene OR	11	2006	60'	New Flyer	NiMH	Diesel
Hartford/Stamford, CT	N/A	2	40'	New Flyer	NiMH	Diesel
Honolulu, HI	N/A	10	60'	New Flyer	NiMH	Diesel
Houston, TX	N/A	4	40'	S&S Repower	NiMH	Diesel
Indianapolis, IN	N/A	2	40'	Gillig		
Louisville, KY	N/A	5	40'	Gillig	NiMH	Diesel
Norwalk, CA	N/A	2	40'	Gillig	NiMH	Diesel
N. Central NJ to New York City	N/A	4	40'	MCI	NiMH	Diesel
Orange County, CA	N/A	2	40'	New Flyer	NiMH	Diesel
Philadelphia, PA	N/A	32	40'	New Flyer	NiMH	Diesel
Pittsburgh, PA	N/A	4	40'	Gillig	NiMH	Diesel
Portland, OR	N/A	2	40'	New Flyer	NiMH	Diesel
San Joaquin, CA	N/A	2	40'	Gillig	NiMH	Diesel
Salt Lake City, UT	N/A	3	40'	New Flyer	NiMH	Diesel
San Juan, Puerto Rico	4 (+10 options)	4	35'	New Flyer	NiMH	Diesel
Seattle/King County	N/A	214	60'	New Flyer	NiMH	Diesel
Seattle/Sound Transit	N/A	22	60'	New Flyer	NiMH	Diesel
Seattle/Sound Transit	N/A	1	40'	New Flyer	NiMH	Diesel
Shreveport, LA	N/A	2	40'	Gillig	NiMH	Diesel
Springfield, MA	N/A	1	40'	Gillig	NiMH	Diesel
St. Paul, MN	N/A	3	40'	Gillig	NiMH	Diesel
Victoria, Canada	N/A	6	12 m.	New Flyer	NiMH	Diesel
Yosemite National Park	N/A	18	40'	Gilllig	NiMH	Diesel
BAE Systems						
New York, NY	325	225 delivered 100, end of 2005	40'	Orion Bus Industries	Lead Acid	Diesel
Roosevelt Island, NY	4	2005/early 2006	40'	Orion Bus	Lead Acid	Diesel
San Francisco, CA	56 + 56 options	2006	40'	Orion Bus	Lead Acid	Diesel
Toronto, Canada	150	2006	40'	Orion Bus	Lead Acid	Diesel
Westchester Co, NY	4	2005/early 2006	40'	Orion Bus	Lead Acid	Diesel
ISE Corporation						
Chicago, IL	10	2006	40'	New Flyer	Ultracapacitor	Diesel
Edmonton, AB	2	2006	40'	New Flyer	Ultracapacitor	Diesel
Elk Grove, CA	21	21	40'	Gillig	Ultracapacitor	Gasoline
Fresno, CA	2 (+options)	2	40'	New Flyer	Ultracapacitor	Gasoline
Gardena, CA	18	Fall 2005	40'	New Flyer	Ultracapacitor	Gasoline
Long Beach	47 + 60 options	47	40'	New Flyer	Ultracapacitor	Gasoline
Montebello, CA	5 (+options)	5	40'	New Flyer	Ultracapacitor	Gasoline
Norwalk, CA	2 (+options)	2	40'	New Flyer	Ultracapacitor	Gasoline
Oakland, CA	10	2006	30'	Van Hool	Undecided	Gasoline
Orange County, CA	2 (+options)	2	40'	New Flyer	Ultracapacitor	Gasoline
Princeton/Trenton, NJ	3	3	40'	Nova Bus	Zebra, converting to ultracap	Diesel
San Bernardino, CA	3 (+options)	3	40'	New Flyer	Ultracapacitor	Gasoline
Azure Dynamics Corporation						
Bronx Clean Commuter Bus	5	1st quarter 2006	22'	Workhouse P42, G1	NiMH	Gasoline
Ebus, Inc.: All Ebus hybrids use either a diesel or propane fueled microturbine						
Coral Gables, FL	N/A	5	22'	Ebus	NiCd	Diesel
Galveston, TX	N/A	3	22'	Ebus	NiCd	Propane
Gulfport/Biloxi, MS	N/A	4	22'	Ebus	NiCd	Propane
Indianapolis, IN	N/A	5	22'	Ebus	NiCd	Diesel
Knoxville, TN	N/A	4	22'	Ebus	NiCd	Propane
Monrovia, CA	N/A	2	22'	Ebus	NiCd	Propane
Muncie, IN	N/A	1	22'	Ebus	NiCd	Diesel
Pasadena, CA	N/A	5	22'	Ebus	NiCd	Diesel
Sevierville, TN	N/A	4	22'	Ebus	NiCd	Propane
Visalia, CA	N/A	3	22'	Ebus	NiCd	Diesel

Fuel Cell Buses

Fuel cells for commercial transportation applications have generated an enormous amount of attention over the last several years, as they offer the promise of a clean, efficient transportation system no longer dependent on petroleum. Fuel cells combine hydrogen and oxygen in an electro-chemical process, with water and heat the only by-products of this electricity generation if pure hydrogen is being used. The production of hydrogen itself can produce emissions, but it is also possible to produce hydrogen from clean sources like wind or solar generated electricity. Fuel cell power is attractive because it provides the potential to dramatically reduce air pollution, greenhouse gas emissions, and petroleum-based energy use. However, transportation fuel cells are still many years away from competing with current transportation technologies, due to cost, robustness and durability, as well as fuel storage issues. In addition, the lack of a hydrogen infrastructure is a deterrent for widespread fuel cell vehicle deployment, as is the expense of, and potential emissions from, hydrogen production. Nevertheless, there is intense interest in pursuing fuel cells as a commercial transportation technology, with major commitments being made by governments around the world to invest in research, development and demonstration of fuel cell and hydrogen technologies. With regard to buses, CARB's Public Transit Fleet Rule requires large fleets to begin deploying zero emission buses in 2008 to 2010, with fuel cell buses seen as the likely solution.

Primer on Fuel Cell Technology for Transit Applications: A propulsion system using a fuel cell as a prime power source directly generates electricity from hydrogen – stored on the vehicle – and oxygen taken from the air. The fuel cell can be used as a stand-alone prime energy source in an electric drive system (essentially replacing the battery) or as the prime power source in a hybrid-electric drive system (replacing the ICE/generator). A fuel cell can be considered similar to a battery in that it produces electrical energy through an electrochemical reaction, not from combustion. Unlike a battery, a fuel cell can produce electricity continuously, without needing to be recharged, as long as it is supplied with hydrogen and oxygen.

Fuel cell buses will require a substantial new infrastructure, with some similarities to that used for compressed or liquefied natural gas buses. The fuel cell powered, electric drive vehicle is very different from the standard diesel bus. Infrastructure, support, and training requirements will depend on what type of fuel is used for the fuel cells. Most demonstrations and available buses use pure hydrogen stored in compressed gas form. Infrastructure will be required for the hydrogen fuel either in bulk storage or for on-site production. Maintenance of the fueling infrastructure will need to be considered as well. As with natural gas fuel systems, the maintenance and vehicle storage facilities will need to be reviewed for mitigation of hydrogen leaks inside buildings. This will mean, at a minimum, proper air ventilation and leak detectors that control emergency equipment inside the buildings as well as explosion proof wiring. Hydrogen has some safety issues beyond natural gas including the potential ability to detonate, rather than just combust. Its ability to embrittle certain metals also needs to be taken into account.

Because hydrogen has different properties than diesel, many modifications will need to be made to the infrastructure, and transit employees will need to be trained to handle this fuel. Transit agencies will need to know the general properties of the fuel, the hazards, how to handle the fuel (fueling, maintenance, emergencies, etc.), and any personal protective equipment needed.

Benefits: Fuel cells offer a number of potential benefits that make them appealing for transit use such as greater efficiency, quiet and smooth operation, and, if pure hydrogen is used on board the bus, zero emissions in operation. While this technology is still in the early stages of development, fuel cells have great potential as a clean and efficient power source. In addition, the fuel cell system will offer the same benefits of any electric drive propulsion system for transit: quicker acceleration, quiet operation (although there is noise associated with the fuel cell system), and extended brake life.

Capital, Maintenance and Operations Costs: Currently, transportation fuel cells are not a commercial product: existing fuel cell buses are prototypes, manufactured in fairly small numbers for specific transit demonstrations. Fuel cell buses today can cost $1 to $3 million (or more) since they are hand-built prototypes utilizing a pre-commercial technology. It is not clear at this time what fuel cell buses' lifetime costs would be. Because of the electric drive system, maintenance costs may be reduced, but it is too early to predict. On-going demonstrations in Europe, U.S., Canada, Japan, Australia and China are expected to yield some data on fuel cell bus operational costs, but as these are still first generation bus technologies, the data will be useful primarily as a general indicator of how transit agencies experience this new technology.

Current Deployments: Currently, there are three major North American fuel cell manufacturers supplying fuel cell powerplants for heavy-duty applications: Ballard Power Systems and Hydrogenics, both based in Canada; and United Technologies Corporation (UTC) Fuel Cells, based in Connecticut. In addition, Toyota has produced its own fuel cell system for heavy-duty vehicles, with a multi-bus demonstration underway in Tokyo.

As noted, fuel cell buses are still pre-commercial products. There are approximately 40 to 50 fuel cell buses in demonstration today, with another five to ten being produced for demonstration in 2005 to 2006. These deployments represent a first generation of heavy-duty fuel cell powerplants, following on progress made in early prototype demonstrations undertaken by Ballard in Chicago and Vancouver in the late 1990s. The following page gives a brief overview of the three North American fuel cell companies currently developing and demonstrating buses. These demonstrations are intended to move fuel cell technology forward to a second and third generation of fuel cell technologies on the pathway to eventual commercialization.

Conclusions: Among the transit professionals interviewed for this report, some view fuel cell buses as the long-term future of low-emission vehicles while others expressed skepticism about the potential commercial viability of fuel cells for the transit market. Because fuel cells offer such great promise for reducing dependence on petroleum and lowering vehicle emissions, they are continuing to be the subject of tremendous private and public sector investment; the recently-passed U.S. Energy Policy Act includes millions of dollars for fuel cell and hydrogen R&D and demonstration efforts. Fuel cell bus demonstrations will continue to help advance the technology, to help reduce costs and increase durability, and will help spur infrastructure deployments. It seems unlikely that fuel cell buses alone will commercialize fuel cells, since the bus market is too small to amortize the tremendous investment made by fuel cell companies. Importantly, hybrid-electric systems are seen as a step on the path to fuel cell buses, as fuel cell systems will need to be hybridized to reach efficiency goals. In addition, further deployment of hybrid buses will help advance the electric drive technologies, and bring down their costs – which will be of benefit to future fuel cell vehicles.

North American Fuel Cell Companies Engaged in Fuel Cell Bus Demonstrations

Ballard Power Systems
Ballard Power Systems partnered with EvoBus, a subsidiary of DaimlerChrysler, to develop a limited series of pre-commercial Citaro fuel cell buses for use in a number of demonstration programs. Ballard supplied heavy-duty (205 kW) Proton Exchange Membrane (PEM) fuel cell engines. As of July 2005, 36 buses have been put into service, logging thousands of miles in revenue service in ten European cities and Perth, Australia. DaimlerChrysler has also delivered three buses to Beijing, to begin a two-year demonstration by September 2005. Ballard plans to develop its second generation fuel cell technology based on lessons learned from these demonstrations.

40-Foot DaimlerChrysler EvoBus with Ballard Fuel Cell in Perth, Western Australia
Courtesy Perth Fuel Cell Bus Project, Government of Western Australia

Ballard also built three 40-foot low-floor buses with Gillig Corporation, using 205 kW fuel cell engines, as part of a multi-agency fuel cell bus demonstration program carried out through the California Fuel Cell Partnership. These buses were delivered to Santa Clara Valley Transportation Authority in early 2005 and are currently undergoing a two-year demonstration.

UTC Fuel Cells
UTC Fuel Cells, based in Connecticut, will be delivering four fuel cell buses for demonstration in revenue service at two California transit agencies, starting in September 2005. Van Hool of Belgium has been contracted to build four 40-foot bus bodies for the fuel cell integration. These buses will be a hybrid configuration with a 120-kilowatt UTC fuel cell and ZEBRA nickel sodium chloride batteries to provide acceleration and hill-climbing power as well as regenerative braking. This program will help demonstrate a hybrid fuel cell system "ruggedized" for transit operations.

40-Foot Van Hool Fuel Cell Prototype Bus with UTC Fuel Cell System
Courtesy ISE Corporation

Hydrogenics
In late 2004, Hickam Air Force Base in Hawaii unveiled a 30-foot shuttle powered with an "automotive-based" fuel cell from Hydrogenics. This configuration employs a very small powered fuel cell – only 20 kW – in a hybrid configuration. The fuel cell does not provide primary power; rather, it charges the main battery propulsion unit and provides limited additional range. The advantage of this configuration is the ability to use the 20-kW fuel cell already in development for the automotive market, which spreads the "return on investment" for the fuel cell company's R&D effort.

30-Foot El Dorado Shuttle Bus with Hydrogenics Fuel Cell at Hickam Air Force Base, Honolulu
Courtesy Hydrogenics Corporation

Hydrogenics is also developing a 40-foot fuel cell bus for demonstration in Winnipeg, Canada in 2006.

Active Fuel Cell Bus Demonstration Programs Worldwide

Note: This list does not include completed fuel cell bus demonstration programs.
( ) indicates that bus has not yet been delivered; green denotes that bus is not yet being manufactured.

Program	Location	Number	Bus Manufacturer	Fuel Cell Manufacturer
Clean Urban Transport for Europe (CUTE) in nine European cities		27	DaimlerChrysler EvoBus	Ballard Power Systems
Ecological City Transport System (ECTOS) in Reykjavik, Iceland		3	DaimlerChrysler EvoBus	Ballard Power Systems
Sustainable Transport Energy for Perth (STEP) in Perth, Australia		3	DaimlerChrysler EvoBus	Ballard Power Systems
California Fuel Cell Partnership (CaFCP)				
	Santa Clara	3	Gillig	Ballard Power Systems
	Oakland (Sept. '05 – Feb. '06	(3)	Van Hool	UTC Fuel Cells
	Palm Springs (Late '05 – Feb. '06)	(1)	Van Hool	UTC Fuel Cells
Natural Resources Canada Fuel Cell Program				
	Winnipeg (May 2006)	(1)	New Flyer	Hydrogenics
Japan Fuel Cell Bus Program				
	Tokyo	8	Hino	Toyota
United Nations Development Program Global Environment Facility (UNDP–GEF)				
	Beijing (Sept. 2005)	(3)	DaimlerChrysler EvoBus	Ballard Power Systems
	Shanghai (date TBD)	(6)		
	Sao Paolo (date TBD)	(8)		
	Mexico City (date TBD)	(10)		
	New Delhi (date TBD)	(8)		
	Cairo (date TBD)	(8)		
Federal Transit Administration - Automotive-Based Fuel Cell Hybrid Bus				
	Honolulu, HI	1	El Dorado	Hydrogenics
	Birmingham, AL (date TBD)	(1)	DaimlerChrysler	Ballard Power Systems
	Newark, DE (date TBD)			
	New Haven, CT (date TBD)			
Federal Transit Administration – Georgetown Fuel Cell Bus Program		5		
	Washington, D.C.	1	NovaBus	Ballard Power Systems
	Washington, D.C.	1	NovaBus	UTC Fuel Cell (PAFC)
	Davis, CA	1	BMI	Fuji (PAFC)
	Jacksonville, FL	1	BMI	Fuji (PAFC)
	Gainesville, FL	1	BMI	Fuji (PAFC)
Miscellaneous Demonstrations				
	Augsburg	1	SGL Carbon AG	Proton Motor Fuel Cell
	Flint, Michigan (Sept. '06 or later)	(1)	Program to issue proposals	
	Munich	1	MAN	Ballard Power Systems
	North-Rhine-Westphalia, Germany Ministry for Transport, Energy & State Planning	1	Tecnobus	Hydrogenics
	Turin (CityCell Program)	1	Irisbus	UTC Fuel Cells
	Victoria/Whistler, BC (2010)	(15-20)	To be determined through bidding process	

Conclusions: Putting the Focus on Hybrid-Electric Buses

Pure battery buses have simply not reached viability for most transit service applications, and so are seen as a niche vehicle. The energy storage capacity and cost of the battery remains the biggest problem – in terms of getting sufficient range, without incurring great weight and cost penalties. In addition, it is not feasible for most transit agencies to place their buses out of service for recharging. Battery buses may still be purchased by users with a need for a zero-emission bus; for example, for buses used indoors or in park areas.

Fuel cells are still seen as the long-term goal by many, with ICE-based hybrids offering a bridge to fuel cell buses. However, there are some in the transit world who see fuel cells as a mirage that is promised but never quite materializes. For those that see them as the long-term solution for vehicle propulsion, the timeframe for truly commercial products is seen as ten years at a minimum, with perhaps commercial fuel cells not being available for another 20 to 25 years.

Hybrid-electric buses have reached the commercial production stage, although hybrid systems continue to be developed and modified. These are no longer primarily demonstration vehicles. We are currently seeing significant increases in hybrid bus orders, some of them going beyond just the small sampling for demonstration purposes and moving into the hundreds (as in Seattle and New York City). Hybrids have been shown to be technically viable for transit service, although there are still some issues to be addressed, such as cost, battery life and longevity of components, which will be discussed in the next section. Overall, however, hybrid buses are a "here now" technology that provide a variety of benefits to transit agencies, their passengers, and surrounding communities. The next sections will provide greater detail on the status of current hybrid bus technology, and the remaining challenges to widespread hybrid bus deployment.

Focus on Hybrid-Electric Transit Buses

The conclusion of the previous section is that hybrid-electric buses offer the best opportunity for electric drive technology to make significant in-roads into transit operations across the U.S. They avoid the range and power problems of pure battery buses, and lessen the burden on transit with regards to implementing new infrastructure. Technologically, hybrid buses are poised to become an equally commercially-viable choice for transit as diesel and compressed natural gas buses. However, while hybrids have demonstrated millions of miles of real-world service, they are still an immature technology relative to diesel and CNG buses. There is no lifetime data on hybrids, so questions of durability, long-term system and subsystem reliability, and lifetime costs are somewhat unclear. In addition, hybrid buses pose some unique regulatory challenges, because of the combination of two different power sources.

Before turning to an examination of barriers to, and benefits of, greater hybrid deployment, it is necessary to look a little more in-depth at hybrid bus technology. This section seeks to provide context for understanding transit and industry representatives' interest in hybrid buses and their concerns about potential barriers to further hybrid bus deployment. This section will speak to hybrid bus technology as it is today, in commercial applications, and, for the sake of simplicity, will focus on full-size hybrid buses of the diesel engine, electric motor, and battery pack variety, as this characterizes the majority of hybrid buses in use today. Information in this section is primarily based on experiences of the 40-foot BAE Systems-Orion buses, the 40-foot and 60-foot GM Allison buses (with New Flyer or MCI chassis), and the 40-foot ISE-Nova buses. This focus should not be taken as a commentary on the other available hybrid technologies that use gasoline engines, microturbines, or ultracapacitors; or on the shuttle bus hybrids.

Emissions and Fuel Economy

The first question to be examined is, what kind of emissions and fuel economy benefits do hybrid-electric buses provide? With regard to emissions, clearly hybrids are not providing the zero emission benefit of battery and fuel cell buses. Nevertheless, laboratory testing on hybrid buses has demonstrated that hybrids offer emissions benefits that are comparable to or better than clean diesel and CNG buses, and a significant improvement over older diesel buses.

Current hybrid bus deployments are carrying out in-use testing to confirm the low emissions of hybrid buses. In an October 2004 presentation to the Society of Automotive Engineers (SAE), New York City Transit reported the following emissions results for the Orion VII hybrid, equipped with BAE Systems' series hybrid drive. The emissions are shown in comparison to a comparable diesel bus with a diesel particulate filter (DPF) and a comparable CNG bus. The emissions results also assume the use of ultra low sulfur diesel fuel.

New York City Transit Orion VII Emissions Comparison				
Emissions in grams per mile	**CO**	**NOx**	**PM/10**	**Total HC**
Diesel with DPF	0.12	2.79	0.2	.02
CNG	2.12	1.89	0.2	1.9 (NMHC)*
Orion VII Hybrid	0.03	0.94	0.2	.02

From New York City Transit, SAE Presentation, October 2004.
*Non-Methane Hydrocarbons (NMHC)

This chart indicates that the Orion VII diesel-hybrids will achieve PM levels comparable to diesel buses equipped with particulate filters (as all 2007 diesel buses will be), and to CNG buses. The Orion VII shows much lower NOx levels than the CNG and diesel buses in this testing effort, although it should be noted that, beginning in 2007, clean diesel buses will be required to meet lower NOx levels than the bus used in these tests.

To date, there is not a lot of official data on in-use emissions from GM Allison buses, as results from on-going tests are not yet complete. The King County transit agency has conducted emissions tests on its GM Allison 60-foot hybrid fleet, but these results have not yet been released. Connecticut Transit (CT Transit) has been testing two 2003 40-foot Allison-New Flyer buses for two years; they are expected to publish emissions results before the end of 2005. CT Transit also conducted emissions analysis for ultrafine particulate matter (less than 100 nanometers) and nanoparticles (less than 50 nanometers). There is concern that these very fine particulate emissions are a greater health problem than larger regulated particles. CT Transit compared the hybrid buses and the 2002 diesel control buses, fueling both with ultra low sulfur diesel. The results were good, with the hybrid buses emitting 12% fewer nanoparticles during the high-speed road tests than the diesel buses.

Fuel Economy: Projections of hybrid bus fuel economy have proven somewhat tricky, as there is limited data from real-world service. Fuel economy estimates based on laboratory testing have typically been overly optimistic, as they don't account for the energy used by vehicle accessories such as air conditioning. However, recently, the National Renewable Energy Laboratory (NREL) released preliminary results from their year-long testing program of the New York City Transit BAE Systems-Orion VII 40-foot hybrids, and the King County, Seattle GM Allison-New Flyer 60-foot hybrids. The Orion VII showed fuel economy improvements of 32% to 48% over comparable diesel buses; CNG buses had lower fuel economy than the diesel buses. The King County hybrid buses showed roughly a 28% to 32% improvement in fuel economy in comparison to diesel buses operating at similar speeds. Hybrids buses operating on a high-speed route showed even better fuel economy, getting about 3.8 mpg in comparison to the diesel buses' 2.4 mpg, although these diesel buses are not operating at a comparable speed as these hybrids. NREL stressed that these are preliminary results, from only a few months of data collection; it could be expected that fuel economy would decrease as the testing moves into warmer summer months when the buses will have greater energy draw from air conditioning. Nevertheless, these initial results are very positive, and do indicate that hybrids will offer transit agencies a benefit over comparable diesel buses in reduced fuel costs.

In CT Transit's hybrid testing program, its 40-foot GM Allison-New Flyer buses are showing varied fuel economy, but on average they are providing only about a 10% to 15% fuel economy increase. In part, this difference in comparison to King County may be due to the lower speed of some of the CT Transit routes, for which the system may not be as fully optimized. In addition, the CT Transit demonstration features one of the earlier versions of the GM Allison hybrid drive. It is important to keep in mind when reviewing testing results that, while hybrid drive is a commercially viable technology, it is still not a fully mature technology. It is likely that, as more in-use experience is accumulated, the hybrid systems will continue to be fine-tuned to achieve greater optimization of the electric drive system, and to hit the right balance between the various trade-offs of power, battery life, fuel economy and emissions. This will also be dependent on the priorities set forth by transit agencies in their procurement specifications.

New Jersey Transit has been conducting fuel economy tests on its two hybrid bus deployments: three 40-foot Nova buses with ISE Corporation's series hybrid drive and ZEBRA nickel-sodium-chloride batteries; and four Motor Coach Industries (MCI) 40-foot buses with GM Allison's parallel drive system. The buses are operating in relatively high-speed suburban routes. New Jersey Transit's test results have shown wildly varying mileage levels for the hybrids, although they are consistently higher than the diesel control buses. The MCI-Allison buses' fuel economy improvements generally fall between 5% and 20%; the Nova-ISE buses' fuel economy increases typically fall between 10% and 30%. New Jersey Transit representatives have not yet determined what is causing the wide range of mileage results.

These results indicate that hybrid buses will provide fuel savings, but the level of savings depends on a number of factors: the hybrid system configuration; the duty cycle, particularly average speed and the level of stop-and-go driving; whether the hybrid system is optimized for peak fuel economy results (as opposed to lower emissions or certain performance characteristics); and, the level of "drain" on the hybrid drive from the bus accessories. These factors will be important in understanding potential cost savings from hybrid bus deployment, as will be explored in the cost section below.

Technical Status: Performance, Reliability and Durability

As a relatively new technology, hybrid-electric drive buses introduce both opportunities and challenges from the standpoint of bus operation and maintenance, and durability of the hybrid drive system. This section will give an overview of results to date on in-service performance and reliability of today's hybrid-electric buses, including a CT Transit survey of passenger and driver reactions to the buses. We will also discuss the question of durability of the hybrid drive system – electric motor, controller, associated components, and, importantly, the battery – in real-world transit service.

Reliability of Today's Hybrid-Electric Buses: Since this is a new technology, and in commercial production at very low numbers, it does not achieve the same reliability as conventional diesel buses, which are a very mature technology. Reports from transit agencies deploying hybrid buses today indicate that hybrids have advanced significantly in terms of reliability, thanks to extensive in-service experience by early adopters like New York City, King County, CT Transit, New Jersey Transit and Southeastern Pennsylvania Public Transportation Authority (SEPTA). Some transit agencies interviewed indicate that hybrid buses are now showing greater reliability than CNG buses did in their comparable state of development.

NREL recently released preliminary results on hybrid bus reliability from the King County Transit data collection program. From July 2004 to February 2005, the hybrid bus road calls closely tracked that of the diesel buses (equipped with the same diesel engine as the hybrids); in fact, the hybrid buses actually went slightly longer between road calls than the diesel throughout much of this period. New York City Transit has reported a goal of 85% availability for their hybrid fleet, and early results showed the new Orion VII buses meeting this goal. New York City Transit representatives have reported that the current fleet of Orion VII hybrids has shown marked improvement in reliability since the initial ten-bus pilot fleet of Orion VI buses; the hybrid buses' Mean Distance Between Failures has improved to where it is roughly comparable to that of diesel buses.

CT Transit has reported very favorable reliability results from its 2003 Allison-New Flyer hybrid bus deployment. Over the two-year demonstration, the average monthly Miles Between Road Calls for the hybrids have been roughly comparable to that of the control diesel buses, with a few exceptions. CT Transit reports that the buses experienced few road calls related to the actual hybrid system, and they have been very pleased to have had no battery problems at all.

Overall, hybrid buses have demonstrated that they can be incorporated successfully into regular revenue service operations, with some issues that would be expected with a new technology.

Performance: Hybrid-electric drive offers enhanced automotive handling performance when compared to conventional mechanical drive due to the characteristics of electric traction motors. Hybrid drive provides smooth acceleration without shifting, a feature that drivers and passengers have responded favorably to in hybrid bus demonstrations around the country. It is also capable of providing faster acceleration due to the increased low-end torque characteristics of electric motors. For example, hybrid bus drivers in New York City have reported that they like the improved acceleration because it helps them pull out into traffic more quickly (although the quicker acceleration has to be limited for the safety of the passengers).

In general, hybrid bus fleet managers interviewed for this analysis reported that they have been pleased with their hybrid buses' performance and with driver and passenger response to the buses. CT Transit conducted surveys of its drivers and passengers to gauge their reaction to the hybrid buses, with positive results. Almost 88% of the passengers surveyed preferred riding in a hybrid to a diesel. While only about 60% were initially aware they were in a hybrid bus, 70% reported that the noise and vibration levels in the hybrid were preferable to that of a diesel bus. 71% of drivers said the hybrids were not hard to get used to driving, while 25% said they had only a little difficulty getting used to the buses. Almost 93% of the drivers said the hybrid buses' acceleration was better than a diesel bus, and 61% found the braking superior; among those that didn't prefer the hybrid to diesel in these categories, most reported that they were the same. Some of the comments received from drivers were that the buses had better pick-up, and don't have as much jerky motion. They reported that it was easier to keep schedule with the hybrids. In all, the driver survey found that 80% of drivers preferred driving the hybrids to diesels.

Durability of Hybrid-Electric Drive Systems: Durability is one of the big question marks for hybrid buses right now, as no agency has had hybrids in service for the 12-year life of a transit bus. Even early hybrid deployments, such as the fleet of BAE Systems-Orion VI buses in New York City in service since 1998, may not yield applicable estimates of durability, as the hybrid technology and integration, as well as the bus design, has changed since this first generation pilot fleet. Going forward, transit agencies will deploy hybrids similar to those being produced today, so the older hybrid experience may not be an accurate predictor of future results, although the expectation is that hybrids have improved since then and will continue to do so. Nevertheless, major questions remain about what to expect in the life of a hybrid transit bus. The biggest concern for transit agencies at this point is the durability of the battery packs. The two battery types being used in commercial buses today are not expected to last for the 12-year useful life of a transit bus. Lead acid batteries are estimated to last about three years in a hybrid bus configuration, while nickel metal hydride batteries are estimated to last about six years. This issue is as much a cost concern as an operational performance concern, and will be discussed in the cost section below. The expectation at this time is that the electric drive components are not a durability concern, as the electric drive has fewer moving parts than an ICE transmission, but this has not been confirmed with long-term revenue service data. There is also some indication that the ICE engine may last longer when used in a hybrid configuration, as the engine does not have to provide all the vehicle propulsion power and will not be used in the extremes as is a diesel bus.

Capital and Operating Costs

This section reviews predicted capital and operating costs for hybrid-electric buses being built today and in the next few years. It is important to note that these are all predictions, particularly the estimates of operating costs, as the current hybrid bus technology (as opposed to the earlier pilot fleets) have had, at most, two years of actual transit experience.

For the purposes of this discussion, capital costs are assumed to include the vehicle purchase price and infrastructure modifications. Operating costs include fuel, parts support (e.g., brakes, batteries), personnel training, labor, and additional insurance. This section will focus mainly on capital costs, as well as the fuel and parts support costs related to a hybrid system.

Hybrid buses today average between $170,000 and $250,000 more than a current diesel bus. Even this is only a rough estimate, as the hybrid bus cost can vary considerably according to the transit agency specifications and the order number. The following table compares these estimated purchase costs for standard 40-foot buses:

Comparison of Estimated Costs of Diesel, CNG and Hybrid Buses

40-Foot Bus Technology	Estimated Cost Per Bus	$ Per Bus Mile (based on 400,000 miles per bus)
2006 Diesel	$280,000 - 290,000	$0.70 - $0.73
2007 Diesel	$300,000 - 320,000	$0.75 - $0.80
Compressed Natural Gas	$330,000 - 360,000	$0.83 - $0.90
Hybrid Diesel-Electric	$450,000 - 530,000	$1.13 - $1.33

There are a few explanations for the cost premium. First, hybrids suffer from the low economies-of-scale that new technologies experience. Most hybrid bus orders are small, and total hybrid bus production is still far below that of conventional buses; as a result, hybrid drive systems are manufactured in, at most, the hundreds at this time. In contrast, the diesel engine industry is well-developed, and the cost of producing transit bus engines is amortized across thousands of engines. There would be an expectation, therefore, that the cost would drop were hybrids in greater production. Indeed, some industry experts think that the electric drive system (excluding the battery) is inherently no more expensive than a diesel ICE system.

A major cost factor at this time is the battery packs, and there is a lot of uncertainty surrounding the expected battery pack life and the cost for replacing them. As already noted, most hybrid buses today use lead acid or nickel-metal hydride battery packs.

BAE Systems uses lead acid batteries in its hybrids. They have estimated that the batteries used for their 40-foot Orion VII buses in New York City have an initial cost of $25,000; replacement costs are indicated to be less than half this cost, as only the batteries are replaced, and not the accompanying packaging and componentry. Current estimates are that these batteries will last about three years. New York City Transit reported that it was getting about 2.5 years on its earlier hybrid fleet, but the current fleet uses different batteries and, more importantly, incorporates significant changes in the hybrid drive optimization strategy, based on their earlier fleet experience. These new hybrid buses have been in service no more than 1.5 years, so there is no real-world data to demonstrate the life of these lead acid battery packs. Lead acid batteries also require periodic conditioning, which will be discussed below under *Infrastructure*.

The GM Allison buses use nickel metal hydride packs. It was difficult to get an accurate estimate for NiMH pack prices, in part because they are not as mature a battery type as lead acid, and there are fewer companies producing them. The range for a NiMH pack appears to be between $35,000 and $45,000. Industry representatives predict that the cost of NiMH batteries will drop as more are produced; in contrast, lead acid batteries are very mature technology and are not expected to drop in price. NiMH batteries are predicted to last from five to seven years. They do not require periodic reconditioning.

As a sample comparison of these batteries types, the table below shows the results of a New York City Transit estimated lifetime cost comparison for lead acid and nickel metal hydride batteries, as well as lithium-ion batteries, which are the advanced battery chemistry being pursued with the greatest interest as a potential replacement for lead acid and nickel metal hydride.

New York City Transit Battery Type Life/Cost Comparison

Chemistry	Lead-Acid	NiMH	Lithium-Ion
Service Life (Expected)	2.5 – 4 yrs	5 – 7 yrs	5 – 10 yrs
Cost ($ / kW-hr)	$100-$150	$300-$500	>> $1000
Life-Cycle Cost ($/kW-hr/Yr)	$25-$60	$42.86-$100	>> $100 – >> $200

It is important to note that there are other considerations besides the upfront and replacement costs of the batteries in determining the best battery type for a hybrid bus. Other important considerations are performance, weight, reliability, and maintenance requirements.

Another important consideration for transit agencies in procuring hybrid buses will be the warranty. Currently, the standard warranty on the batteries is two years; this will not cover replacement of the battery pack, which then becomes an additional operating cost for the agency. Some hybrid bus procurements have been negotiated with longer warranties for the battery packs, which could then move the battery replacement cost to an upfront capital expense. Each agency will have to make a determination about how to address this issue.

In short, the durability and replacement costs for batteries represent a significant unknown factor for transit agencies at this time, and will continue to be unknowns until there is long-term operating data on these vehicles. Hybrid drive companies and their bus company partners are currently exploring innovative ways to address this cost concern for transit agencies.

Infrastructure Costs: Although hybrid buses utilize the same fueling infrastructure already in place for existing diesel or gas fleets, there are a few modifications required for maintenance facilities; these will add to the overall cost differential between diesel/gas buses and hybrids.

Maintenance upgrades might include the need for lifts or cranes for trading out battery packs, and safety equipment for working with high voltage electrical systems. Transit agencies that purchase hybrid buses equipped with lead acid batteries will also have to purchase battery charging/conditioning units. New York City Transit reports that they recondition their batteries once every six months, with the buses out for a 20-hour cycle. The charging units can cost around $50,000. Nickel metal hydride batteries do not require reconditioning.

Fueling Costs: One of the cost advantages that hybrid buses offer is, of course, reduced fuel use. It is difficult to estimate the fuel savings over the lifetime of a hybrid bus, in part because the future direction of diesel prices is an unknown, although the current trend is upward. The following table compares the fueling costs for ultra-low sulfur diesel, CNG and hybrid-electric diesel, using the early fuel economy results, reported by NREL in May 2005, of the New York City Transit Orion VII buses against comparable diesel and CNG buses. This chart is intended only as an example of fuel savings that might be expected. Hybrid buses' fuel economy will vary, as will diesel and natural gas prices. These fuel cost estimates are based on Energy Information Administration "commercial fuel" prices as of July, 2005; transit agencies will have different prices based on regional price differences and each agency's negotiated long-term contracts.)

Sample Comparison of Fuel Costs Using Preliminary Fuel Economy Results from NREL New York City Transit Testing Program

	Diesel	**Hybrid-Electric**	**CNG**
Fuel Costs	$2.40/gal.	$2.40/gal	$1.19 - $1.50/equiv gal
Fuel Usage	2.5 mpg	3.5 mpg	1.7 mpg
Per Mile Cost	$0.96	$0.68	$0.70 - $0.88

System Maintenance Costs: Again, it is still too early to estimate the difference between diesel or gas buses and hybrids in maintenance costs over the life of the bus. One major benefit for hybrid buses is extended brake life, as the electric drive system and regenerative braking mean less wear-and-tear on the brakes. Transit agencies deploying hybrids are reporting that the hybrid buses may extend brake life by 50% to 100% (or more). Hybrid buses also may put less "stress" on the engine, as the engine is operating in a more efficient range; it is possible that this could reduce the engine repower or rebuild costs, although this is only speculative at this point. Finally, the electric drive components may require less maintenance and last longer than the transmission and its related parts.

Estimated Combined Fueling and Maintenance Costs: NREL is examining maintenance costs for the King County hybrid bus fleet, compared to those of diesel buses on a cost per mile basis. In their presentation of their preliminary results, NREL combined fueling and maintenance costs to provide an estimate for comparing the hybrid buses with comparable diesel buses. King County is operating two fleets of hybrids, in different duty cycles, so the hybrid results are separated according to the fleet base.

Early Results for King County Evaluation Buses: Fuel and Maintenance Cost Per Mile

	Diesel (Ryerson Base) Avg. speed 13.3 mph	Hybrid (Atlantic Base) Avg. speed 11.2 mph	Hybrid (South Base) Avg. speed 19.2 mph
Fuel ($1.47/gallon)	$0.614/mi – 2.39 mpg	$0.466/mi – 3.15 mpg	$0.396/mi – 3.72 mpg
Maintenance	$0.433/mi	$0.456/mi	$0.396/mi
Total	$1.047/mi	$0.922/mi	$0.792/mi

From NREL Presentation to APTA, May 2005.

If these costs are extrapolated out over the life of the bus, assuming that a typical transit bus runs for 400,000 miles over its 12-year life, deploying a hybrid bus out of the Atlantic Base would result in a fuel and maintenance savings of $50,000 over diesel buses in the Ryerson Base, while a South Base bus would achieve fuel and maintenance savings of $102,000 (see chart below).

Sample Comparison of Fuel and Maintenance Costs Over 12-Year Bus Life Using NREL King County Preliminary Data			
Costs For 400,000 Miles of Operation	Diesel (Ryerson Base) Avg. speed 13.3 mph	Hybrid (Atlantic Base) Avg. speed 11.2 mph	Hybrid (South Base) Avg. speed 19.2 mph
Fuel	$245,600	$186,400	$158,400
Maintenance	$173,200	$182,400	$158,400
Combined	$418,800	$368,800	$316,800

However, these estimates do not take into account the additional cost of battery replacement, which is expected to be a significant expense. In addition, it is difficult, if not impossible, to extrapolate fueling and maintenance estimates for one type of hybrid bus in a certain agency's service to a different hybrid bus placed in another type of service. Fueling and operational costs are variable, dependent on the hybrid system architecture, the overall bus efficiency, the bus' duty cycle, and the local climate. At this time, transit agencies will have to make a best estimate of lifecycle costs when making procurement decisions. Some of the factors to consider when comparing operational costs of a hybrid bus to a diesel bus are as follows:

Hybrid-Electric Transit Bus Characteristics That May Affect Lifecycle Cost Comparisons with Diesel Buses
· Hybrid System Architecture: Series, Parallel, Overall System Optimization · Battery Type: Added Cost for Battery Replacement; Battery Conditioning For Lead Acid Only · Duty Cycle: Stop-and-Go, High- or Low-Speed · Overall Vehicle Efficiency, Especially Efficiency of Accessories · Fuel Savings: Depend on Hybrid System Efficiency and Optimization, Overall Vehicle Efficiency, Applicability of Hybrid System to the Duty Cycle · Engine Repower or Rebuild Costs May Be Reduced With Hybrids · Brake Life May Be Extended · Maintenance for Transmission Not Needed for Series Hybrid

Deployment Issues: Training, Maintenance and Safety

For any electric drive bus, support and training in understanding high voltage vehicle systems safety is required. There is a need for mechanic training in how to service and troubleshoot electric propulsion components, and understanding how to work with the on-board diagnostics systems. While transit agencies that operate rail systems are familiar with the requirements of operating and maintaining high voltage electrical propulsion systems, there is often no overlap between the maintenance staff for rail and for buses. In addition, lead acid batteries must be reconditioned about every six months, which will require some staff training. There may also be a need for an overhead crane for any roof top units such as battery packs, or a standard forklift may be sufficient for lifting out the battery pack from the bus. Maintenance staff should be protected from potential falls while performing maintenance on the rooftop componentry. Thus far, drivers seem to adapt to the hybrid buses well, and do not require extensive training. For a more in-depth overview of safety guidelines for transit systems using electric drive, see the FTA Report *Design Guidelines for Bus Transit Systems Using Electric and Hybrid Electric Propulsion as an Alternative Fuel*.

Regulatory Status

Emissions certification of trucks and buses presently involves testing of the engine only. The Engine Compliance Program at the EPA Office of Transportation and Air Quality is responsible for certifying engines for heavy-duty applications. The CARB Mobile Sources Control Division performs a similar function for certification in the California. Both EPA and CARB use the same test procedures for urban bus engine certification: engines are certified on the Federal Test Procedure (FTP) transient cycle. Emissions are measured and reported in units of grams of emissions per brake horsepower hour (g/bhp-hr) delivered by the engine under specific load regimes. The emissions are not allowed to exceed certain standards set by EPA and California. Engine manufacturers are responsible for complying with exhaust emission standards.

This poses an issue for hybrid buses, as the engine tests do not accurately reflect the emissions from the total hybrid system. Chassis testing is the only way to accurately determine hybrid bus emissions, but chassis-based emissions testing in the United States only occurs on light duty vehicles (except in California where chassis-based certification of medium-duty vehicles is allowed). In an effort to address this concern, California adopted an interim testing procedure for hybrids which allows manufacturers to use a hybrid bus factor in reporting emissions from hybrid buses. Manufacturers are required to show test results that support their claims for reduced hybrid bus emissions. This Interim Procedure is set to expire in 2006.

At this time, the EPA does not have any testing procedure that allows for hybrids to be treated differently than other transit buses. Hybrid buses must use EPA-certified engines in their propulsion system in order to meet EPA requirements. It is not possible for hybrid bus users to certify their hybrid drive system (as opposed to the engine) to the EPA standards, nor is it possible for them to get credit for greater emissions reductions experienced by the hybrid buses. EPA recently announced that it is starting a pilot program of in-use emissions testing on trucks and buses; it is not known whether this will become the standard procedure for certification.

Hybrid Bus Tax Credits

The recently-passed U.S. Energy Policy includes new tax credits for hybrid bus purchases. Beginning with 2006 bus deliveries, hybrid vehicles with a gross vehicle rating of more than 26,000 pounds qualify for tax credits of 20%, 30% or 40% of the vehicle’s incremental cost; however, only up to $30,000 in incremental costs qualifies. A vehicle with a city fuel economy improvement greater than 30% but less than 40%, receives a 20% tax credit on the incremental cost. A vehicle with a city fuel economy improvement greater than 40% but less than 50%, receives a 30% tax credit on the incremental cost. A vehicle with a city fuel economy improvement of at least 50% receives a 40% tax credit on the incremental cost. If the buses are purchased by a tax-exempt organizations, the bus seller can claim the tax credits as long as the seller notifies the purchaser in writing of said tax credits to be claimed. The tax credits are in place until December 31, 2009.

Estimated Tax Credits for Hybrid Vehicles Over 26,000 Pounds GVW		
Fuel Economy (FE) Increase	%	Total, assuming $30,000 incremental cost
30% ≤ FE increase < 40%	20%	$ 6,000
40% ≤ FE increase < 50%	30%	$ 9,000
50% ≤ FE increase	40%	$12,000

Benefits of Wider Hybrid-Electric Transit Bus Deployment

Hybrid buses offer significant benefits to both the transit operators and the community at large. This section will review the benefits to transit and to communities if more transit fleets adopt hybrid buses in greater numbers over the next decade. There is overlap between transit agency benefits and community benefits, as transit operators must comply with environmental regulations and also strive to be "good neighbors." This discussion is based on input from transit agencies interviewed for this analysis, as well as the input from other stakeholders and general research of the technology. It is important to understand the value of hybrids to transit operators when discussing the potential barriers to hybrid deployment and how best to address them.

Reduced Emissions: Hybrid buses are appealing because they have lower NOx and CO levels than current diesel and compressed natural gas buses; lower particulate PM emissions than current diesel buses; and comparable PM levels to CNG and to diesel buses equipped with particulate filters. For transit agencies in nonattainment areas, adopting hybrids can help contribute to a coordinated effort to bring the region into compliance. For transit agencies in California, diesel-hybrid buses are a key component in the clean diesel path under CARB's Public Transit Bus Fleet Rule, and gasoline-hybrids can be used in compliance with both the diesel and alternative fuel path.

Lower Infrastructure Costs Compared to Other Low Emission Technologies: For transit agencies looking to reduce the emissions footprint of their fleet, the best options – until the new diesel rules go into effect in 2007 – are CNG and hybrid. These two technologies offer the greatest reductions in PM and NOx. However, CNG requires an entirely new, and expensive, infrastructure. Transit agencies have adopted hybrids because they offer similarly low emissions, but without the major infrastructure investment. Hybrid buses utilize existing diesel and gasoline fueling infrastructure. No commercially available hybrid bus today requires battery charging, as pure battery buses do, as this is not acceptable for the vast majority of transit operations. Hybrids do bring some new infrastructure requirements relating to the batteries and the electric drive system overall, but these cost only a fraction of what the CNG infrastructure costs. Also, because hybrids can use existing infrastructure, it is economically feasible for transit agencies to test a small number of hybrids before committing to a major purchase, or to slowly transfer their fleet from conventional diesel to hybrid.

Reduced Fuel Use: The potential to cut fuel costs over the life of the bus holds appeal to transit agencies, which must focus on the bottom line for their transit operations. The fuel economy benefit varies significantly among the different hybrid technologies, but all are designed to offer some level of increased fuel efficiency. Transit operators interviewed for this analysis generally agreed that fuel economy is an important benefit, but that it still secondary at this point to the emissions benefit. At this point, the reduced fuel costs over the lifetime of the bus do not pay back the initial premium paid for the bus purchase. If the price of diesel fuel continues to rise, transit agencies with hybrid buses will be better positioned to adapt.

Reduced Noise Makes Transit a Good Neighbor: While most attention is focused on cleaning up the tailpipe emissions of buses, noise pollution is often as important an issue to transit passengers and people in surrounding communities. Indeed some transit operators noted that noise may become the next pollution issue with communities concerned about negative impacts from local bus operations. Hybrids are quieter than conventional diesel buses, and some transit agencies cited the noise reduction as an important factor driving their interest in hybrids.

Better Acceleration From Stops: Hybrid buses feature quicker acceleration from a stop than diesel buses do. Transit bus drivers are always striving to stay on a tight schedule, and transit agencies using hybrids have reported that the hybrids reduce "dwell time," making it easier for drivers to stay on schedule, or even get ahead of schedule. King County Transit has even reported that the reduced driving time may allow the agency to use fewer buses on a route.

Reduced Maintenance Costs: Hybrid buses offer the potential for lower maintenance costs over the life of the vehicle, related to the engine and the braking system. Transit operators that have deployed hybrids are reporting some reduced maintenance; however, hybrids are still a new technology, and there is no data yet on the lifetime costs of hybrid buses. So the projections of lower lifetime maintenance costs are just that – projections. In addition, as hybrids are not yet standard in the transit world, an agency that adopts hybrid buses will have some additional expenses initially, primarily related to training of drivers and maintenance workers. Nevertheless, hybrid bus operators are reporting that the buses are showing promise to reduce lifetime costs for the engine maintenance, due to greater steady state operations. Hybrids also put significantly less wear-and-tear on the brakes, and may extend brake life by 50% to 100%.

Pathway to Fuel Cells: For those that are looking to fuel cells as the long-term answer to transportation security, hybrids are seen as a step in this direction. Experiences with fuel cell bus development and demonstrations to date have led the fuel cell industry to conclude that fuel cell buses must be hybridized in order to derive the greatest energy efficiency benefits from the fuel cell system. A hybridized system also serves to minimize the power output requirements of the fuel cell, thus minimizing size, weight and cost of the fuel cell. In addition, development of the electrical systems for hybrid buses – including advanced controls, diagnostics and electric accessories – will translate into a benefit for hybridized fuel cell systems, as they can capitalize on knowledge gained from hybrid deployments. The efforts to make electric drive system more efficient will be of particular benefit to fuel cell advancement, as a more efficient electric drive could allow for smaller – and, therefore, cheaper and lighter – fuel cell stacks. In addition, by deploying hybrid buses now, transit agencies will learn more about how to maintain and operate the electrical systems, which will give them a headstart in deploying fuel cells.

Barriers or Challenges to Widespread Deployment of Hybrid-Electric Transit Buses

The industry participants for this report were asked for their view of the chief barriers to greater deployment of hybrid buses in the U.S. They were specifically asked about technical, cost, regulatory and institutional barriers to hybrid bus purchases.

Technical Challenges

At this point, there are no major technical roadblocks to widespread commercialization of diesel-hybrid buses. This was the majority viewpoint from industry representatives who participated in this report. Clearly, the experience of New York City Transit and King County, with their major hybrid demonstration and deployment efforts, have not only helped advance the technology, but also have confirmed that hybrid buses are "ready for prime time."

This is a significant difference between diesel-hybrid buses and the other two electric drive bus options, pure battery and fuel cell. Battery buses simply have not proven any ability to fill the drive cycle requirements of most transit agencies, due to their range and weight issues. Fuel cell buses are still in the research and development phase, with only demonstrations designed to prove, and improve, the technology at this point. By contrast, with over 40 transit agencies incorporating hybrids into their fleets as of mid-2005, hybrid-electric buses have demonstrated that they are capable of performing in real-world transit service, in a range of operational conditions.

It should be noted that, while the industry representatives who were interviewed for this report largely attested to the technical viability of hybrid buses, most transit agencies are still only "testing the waters" by deploying a handful of hybrids. One important reason for this is the high cost of hybrids, but these transit agencies also expressly stated that they want to try out the hybrids in their system before committing to large procurements. Agencies like Connecticut Transit, New Jersey Transit, and some others with small hybrid deployments have indicated they are looking to expand their hybrid fleet slowly, based on the performance of these small test fleets. They have also indicated that the hybrids have performed up to expectations, and that they have not found any major technical issues that would stand in the way of greater procurements. Other agencies are jumping in enthusiastically, based on the success of the New York City Transit and King County hybrid programs.

While hybrids have proven commercial viability, they are still a "work-in-progress". Hybrid system manufacturers and transit agencies alike will be learning from current and pending hybrid bus deployments over the next few years. While there are no "showstoppers" for hybrid buses, many industry representatives noted that hybrid buses still require improvements in three technology areas:

> *Energy storage:* The biggest technology concern surrounds the battery packs. It is simply not known how long today's hybrid bus battery packs will last, which leads to concern about replacement costs. Lead-acid battery packs are estimated last three years on the Orion VII production fleet. Nickel metal hydride packs are estimated to last five to seven years in hybrid bus operations. Neither of these claims has been proven in real transit operations. This issue is where technical concerns intersect with cost barriers, as battery packs are

expensive and will significantly increase the lifetime costs of the bus; there is more discussion of this issue in the Cost Barriers section below. Cost is not the only factor driving battery selection: weight, reliability, and performance are also important considerations. Hybrid system developers are exploring more advanced energy storage options, such as lithium batteries and ultracapacitors, in an effort to find a solution that will meet transit agency needs in terms of performance, reliability, durability and cost.

Electrically-Driven Accessories: Some transit agencies have indicated that there needs to be more work on developing and implementing electrically-driven accessories for hybrid buses. Current bus auxiliary systems have been designed for diesel ICE buses; these systems are not optimal for electrically-driven buses. While systems integration is always a concern, when properly selected, sized, integrated, managed and controlled, electrically driven accessories have the potential to significantly increase overall fuel efficiency and reliability compared to mechanically-driven counterparts.

On-Board Diagnostics: Hybrid buses have sophisticated electronic systems that change the nature of diagnosing problems and trouble-shooting. Although clean diesel buses also feature increasingly complex on-board systems, hybrid buses require better and more sophisticated on-board diagnostics to allow transit operators to predict, prevent, or resolve problems.

Cost Barriers

The clear consensus view of our interview subjects was that the high capital cost of hybrid buses is the biggest barrier to greater hybrid transit bus commercialization. As was noted in the *Review of Hybrid-Electric Transit Buses* section, a 40-foot hybrid bus today typically costs somewhere between $170,000 to $250,000 more than a comparable 40-foot diesel bus. While much of this difference can be attributed to the lack of economies-of-scale, this differential will not disappear if hybrid buses become more widespread. The transit bus market in the U.S. is about 5,000 units per year; this is not a sufficient number to bring down the price of hybrid buses to compete with diesel bus prices. For hybrids to be truly cost competitive, the hybrid technology will have to migrate into larger markets, such as the medium and heavy-duty truck markets.

In the meantime, for transit agencies operating within strict financial limitations, it is difficult to justify such a significant differential in upfront capital costs. Of course, the cost considerations for buses include the lifetime costs, of fueling, maintenance, and additional capital acquisitions such as battery replacement. Understanding the lifetime costs of hybrid buses is an important consideration for transit operators who are interested in purchasing hybrid buses instead of diesel, and need to justify the additional upfront cost to their boards. Increased fuel economy will translate into lower lifetime fuel costs for hybrids buses; however, right now, hybrids are not providing sufficiently increased fuel economy to offset the 60% (or more) increase in purchase price. Accurate numbers on hybrid buses' fuel economy can be hard to come by, but data from current hybrid bus deployments show the buses getting approximately 10% to 50% better fuel economy. This is not currently sufficient to offset the higher purchase price. Transit agencies that we spoke with gave varying estimates for the break-even price for hybrid buses; a typical estimate, at current diesel prices, was that a 30% initial cost premium would be offset over the 12-year life of a bus. Alternatively, at current hybrid bus prices, the price of diesel would have to rise above $4.00/gallon for the lifetime fuel savings to offset the purchase price differential.

In addition to purchase price and fuel savings, hybrid buses will differ from diesel in lifetime costs in other respects, both positive and negative. On the negative side, transit agencies that purchase hybrid buses must also budget for battery replacement. As noted above, this is where technical issues intersect with cost concerns. Currently, lead acid battery packs in transit service are estimated to last for approximately three years; NiMH packs are estimated to last five to seven years. BAE Systems reports that the batteries used for their 40-foot Orion VII buses in New York City have an initial cost of $25,000, with significantly lower replacement costs. NiMH packs are estimated to cost between $35,000 and $45,000, although it is difficult to get definitive numbers as this is not an off-the-shelf technology.

Ultimately, durability and replacement costs for hybrid buses' battery packs are an unknown factor for transit agencies until there is long-term operating data on these vehicles. One key element for agencies will be the warranty offered on the battery packs. In addition, hybrid drive companies are exploring innovative ways to address this cost concern for transit agencies.

On the positive side, it is expected that hybrid buses will put less wear-and-tear on transit buses' brake systems, requiring less frequent replacement of the brakes. Because the hybrids depend less on the diesel engine for their motive power and utilize regenerative braking, the bus operations are less hard on the brakes. In addition, hybrid buses may have lower maintenance costs than diesel, as the electric drive components require less maintenance than the diesel transmission system. Also, early indications are that agencies may save on engine rebuild and replacement, as there is less stress put on the engine in hybrid operations.

In conclusion, at this time, in spite of the fuel savings and potential maintenance savings, estimated lifetime costs of hybrid buses are still too high to make them cost-competitive with diesel buses. There a couple of different angles from which to look resolve this problem. The cost of hybrids can come down, the price of diesel fuel may increase significantly, and the price of 2007 to 2010 diesel buses may increase and reduce the differential.

The example of the King County buses' fuel economy and maintenance costs described earlier show hybrids saving $50,000 in fueling and maintenance costs over a 12-year bus life; reducing the hybrid price premium to $50,000 would be the "break-even" point. Alternatively, we can use the same fuel economy and maintenance estimates, but assume an increase in diesel prices to $4.00/gallon. At this fuel price, using the NREL preliminary King County data as an example, an initial capital cost of approximately $150,000 would be "paid back" over the life of the bus.

However, even if hybrid buses do become competitive with diesel on a lifecycle cost basis, current FTA funding requirements will not allow a transit agency to consider the lifetime costs when awarding a low-bid procurement.

Finally, a key concern here for transit agencies is risk management, as they will have to place hybrids in their fleets with some uncertainty about the total life cycle costs. This may be a major barrier for risk-averse transit agencies.

Emissions Certification and Testing Challenges

As already noted, emissions certification of trucks and buses presently involves testing of the engine only. Industry and regulators have recognized for some time the unique challenge posed by hybrids in the emissions certification process compared to traditional transit buses. There are two problems that result from the incompatibility of current emissions certification procedures and hybrid bus systems. First, it is not possible to credit hybrid bus users with the full emissions reductions experienced by hybrid bus deployment. Second, hybrid systems cannot use smaller engines that are not certified for transit use in spite of the fact that the overall hybrid bus emissions would meet or exceed the EPA emissions requirements.

There are a few practical effects of these issues. Because hybrids are not being fully credited for their emissions reductions, they lose this competitive advantage over diesels. When the 2007 diesel regulations come into effect, if diesel buses are able to meet the very low NOx and PM standards, a transit agency may have trouble justifying the additional expense of a hybrid, given that they are unable to receive credit for the even-lower emissions of the hybrid bus. Unless the price premium for hybrids drops to $90,000 or lower, or the price of diesel rises to $4.00/gallon, it appears that the hybrid bus will not have lower lifecycle costs than a diesel bus. Therefore, getting full credit for the hybrid bus emissions will be crucial to ensuring that hybrids can be competitive with 2007 diesel buses. It should be noted that, if diesel engine manufacturers and bus companies have difficulty complying with the 2007 to 2010 regulations, and either choose not to offer products or offer products with reduced performance and reliability, hybrid buses will benefit from a comparison with diesel.

The other major practical effect is that the current engine certification requirements hamper the ability of hybrid developers to take full advantage of the hybrid system by using smaller engines than are certified for use in transit buses. Because hybrids are not relying only on the engine for power, but instead use the electric drive system for acceleration and hill-climbing, they can use smaller diesel engines and still successfully meet transit drive cycle needs. Using a smaller engine would allow the hybrid system to achieve even greater fuel economy. This benefit would be lost if hybrid developers are required to use full-size transit engines in their systems.

The challenge is for regulators to determine how to properly credit hybrids with their emissions and fuel economy savings, without unduly burdening bus manufacturers with the certification requirements. Currently, the cost of certifying heavy-duty engines is amortized across thousands of engines; the cost to certify a hybrid system would only be amortized across a few hundred hybrid systems at this point. One option would be to seek an alternate engine cycle on which to test hybrid engines for purposes of emissions certification. Another option is to adopt some kind of “factoring” procedure as CARB has done.

Institutional Barriers

Transit agencies gave mixed messages about any potential institutional barriers to further hybrid deployments. Institutional barriers refers to barriers within transit agencies not related to practical concerns such as cost or performance; for instance, a predisposition to prefer diesel or CNG buses to hybrids, or a fear of high voltage electrical systems. While many respondents indicated that there were no major institutional barriers at this time, some felt that the generally conservative nature of transit agencies might slow further adoption of a new technology like hybrid buses. This may be a particular concern given the lack of real-world data on hybrid buses’ durability and lifetime costs. Others indicated that transit agencies may be wary of maintaining and operating the high voltage electrical systems. And, many small transit agencies do not have access to complete information about hybrid bus technologies, their benefits and drawbacks, and their maintenance and training requirements.

Industry View on Addressing Barriers to Greater Hybrid-Electric Transit Bus Deployment

The following list is based on the NAVC's interviews with stakeholders in the electric drive bus world, as well as feedback from a meeting of hybrid bus stakeholders held on May 14, 2005 in conjunction with the APTA Bus and Paratransit Conference in Columbus, Ohio. These items are sorted into the following four broad categories, depending on which issue they seek to address: cost, technology, information, and certification and emissions testing.

Addressing Cost Issues:

The development and adoption of a validated life cycle cost or cost of ownership method of procurement which could be applied to capital equipment procurements.
All interview subjects agreed that it is important to evaluate cost of bus technologies on a life-cycle basis; most, though not all, felt that a revision to FTA procurement requirements to allow transit properties to compare bus proposals by life-cycle costs, rather than capital costs only. Hybrid buses will continue to have higher upfront costs than conventional diesel, but these costs can be offset by the reduction in fuel use over the life of the bus; evaluating buses according to capital costs only will provide a distorted advantage to conventional diesel buses. While many of the interview subjects said they do not believe hybrid buses' reduced fuel use will completely offset the initial cost premium, it will significantly reduce the overall cost differential between hybrids and diesel buses.

The difficulty with this idea will be determining how to verify fuel savings claims made by manufacturers or transit agencies and how to hold manufacturers accountable for such claims. It may be necessary to require manufacturers to provide warranties to support lifecycle cost claims.

Provide greater FTA share to cover the cost differential between hybrid and diesel buses.
All the transit properties cited cost as the main barrier to increased purchase of hybrid buses. They stressed the need for greater government support to offset the initial cost premium of hybrids. One suggestion was to increase the federal share for hybrids to 90 or 95%.

Support a revival of the Alternative Fuels Initiative program – or a comparable program – that will be targeted specifically to hybrid buses.
Hybrid system manufacturers are looking to recoup considerable R&D investment, and, while the number of hybrid buses on order represent a significant move forward, the market is still not sufficient to make the business case for hybrid developers. Some have mentioned that the Alternative Fuels Initiative program in the 1980s was a major factor in moving CNG buses from "test and demonstration" technology to a commercially viable technology. It was suggested that a similar program be targeted for hybrid buses, to encourage transit agencies to purchase hybrids over the next few years, until the hybrid market can become more self-sustaining.

Provide for capitalization of energy storage systems during the life of the vehicle or provide financial incentives to promote the use of more robust and durable energy storage systems.
The need to replace energy storage systems during the life of the bus, and the uncertainty surrounding the cost and durability of these systems, was another major cost concern for transit properties considering greater hybrid deployment.

Create a depreciation "credit" for buses under 12 years old.
Interest in changing the definition of "useful life" for new bus technology was mixed; however, some transit industry representatives suggested that a depreciation credit that kicks in prior to the 12-year mark would help offset the burden of adopting new technologies, especially as these technologies are continually progressing, making relatively "young" buses obsolete. They felt there could be a way to provide for the maturation process of a technology related to other goals such as improved fuel economy and emissions reductions; for example, if transit agencies received credits based on meeting certain targets for these criteria set by FTA.

Addressing Technology Issues:

Provide continued funding support for testing and validation of improved energy storage for hybrid-electric bus applications.
Energy storage devices – in particular, batteries – continue to be the biggest technical challenge for hybrid buses. Industry interest is not in government funding for basic battery research, but rather to fund validation and testing of integration and demonstration of advanced storage media in hybrid-electric drive for transit applications.

Provide funding for continued integration of, and improved options for, electrically-driven accessories and on-board diagnostics.
While not as critical as energy storage development, electrically-driven accessories and on-board diagnostics were cited as two areas that need technical improvements in order to make hybrid buses more commercially viable. Electrically driven accessories are more efficient than conventional accessories; given the need to use on-board energy storage in the most efficient manner possible, it is important to make the best use of the availability of electrically-driven accessories. In addition, the multitude of electrical systems, operated by complicated computer software programs, requires on-board diagnostics systems that can alert operators to potential problems, and pinpoint the source of problems when they occur. This will help reduce any down time for hybrid buses, a critical factor in making hybrids viable and competitive with conventional diesel buses.

Provide some additional maintenance and training resources during the initial deployment of hybrid technologies to preclude lack of knowledge from causing program failure.
While most transit properties and hybrid system manufacturers said that training should be the primary responsibility of the hybrid companies, a few said that it could be useful, in the early stages of hybrid deployment, to have a generic education and training program sponsored by FTA. Some interview subjects indicated that they thought fear or ignorance of electric technologies is a barrier to greater hybrid deployment. Some transit representatives thought that an FTA-sponsored training program would introduce other transit properties to electric drive technologies and the major maintenance and training issues involved with the technology. Currently, transit operators rely on the few properties who have hybrids to learn more about the technology; FTA could sponsor a one-day program for any interested transit property to learn more about electric drive systems.

Promote technologies that reduce noise emissions from buses and vehicle systems.
It was noted that transit customers have responded very favorably to the reduced noise emissions from hybrid buses. While this was not the primary intended benefit of hybrids, it is one of the most publicly noted ones, and can help encourage greater use of transit services in general.

Addressing Information-Related Issues:

Support a synthesis of the state of the technology that could provide a validated set of information that transit properties could use in decision-making procedures for capital equipment.
Many transit agencies emphasized the need for objective information on the various hybrid technologies currently available. In particular, there was much discussion of the differences between series and parallel hybrid technologies. Transit operators said it would be beneficial to have a source of information other than the manufacturers, and that would be easily understood by transit properties that may not be familiar with hybrid technology and the differences among the various configurations. This synthesis would not advocate for one particular technology over another, but would clearly explain the differences.

Provide a resource for information from other sectors of government where similar research, testing, or deployment of technologies is occurring.
Several transit properties said that various government agencies do not always communicate and share information well, and it can be difficult to keep track of all research, testing or deployment activities being undertaken at various agencies. Some felt that a centralized information base for government activities would be helpful.

Improve coordination of myriad government agency programs for hybrid buses.
Industry believes that all government agencies should work to coordinate demonstration and deployment programs, in order to avoid duplication and to leverage public funds for the greatest benefit.

Addressing Certification and Emissions Testing Issues:

Support a tailpipe emission certification process for heavy-duty vehicles.
Currently, hybrids cannot be certified as a whole system to EPA's emissions standards. Rather, the hybrid system just uses an urban-bus certified engine to comply with EPA standards. Some interview subjects said that it should be possible to certify hybrids on a system basis, rather than an engine basis, because the engine certification does not provide an accurate picture of the hybrid bus's emissions. However, there were others who did not think this issue was a particular barrier to greater hybrid deployment. They felt that hybrid buses would simply continue to use urban bus certified engines in order to meet the certification procedures until bus and truck emission regulations homogenize in 2007. In addition, bus companies indicated that it would be too cumbersome to take over the certification process and liability, unless they were allowed to certify a particular engine and hybrid system configuration for many different bus systems. It is important to note, though, that it is possible that the current certification procedure will hinder hybrid buses competitively.

Support development of verification procedure for hybrid buses.
Some interview subjects thought that a verification procedure could be an alternative to developing a new certification process, or at least as an interim step that could be taken while a new certification process is developed. Hybrid bus stakeholders suggested that, in the absence of a more accurate, EPA-approved method for certifying hybrid bus emissions, it would be beneficial for EPA to have a method to "verify" hybrid bus emissions. A verification procedure would allow transit agencies to use hybrid bus acquisitions as part of their state's State Implementation Plan (SIP), required to demonstrate compliance with EPA's attainment standards. Establishing a verification procedure would be a less difficult and prolonged process than establishing a new certification procedure, as it does not require rulemaking process. One option would be to adopt a variation of CARB's Interim Certification Procedure for hybrid buses, which uses a hybrid bus emissions factor to estimate the lower emissions resulting from a hybrid bus.

Support revision of the SAE emissions testing standard.
Several interview subjects noted that J2711, the SAE standard for heavy duty hybrid bus emissions and fuel economy testing, needs to be updated to include testing of accessory systems such as air-conditioning. Testing that uses J2711 has shown some significant divergence from real-world emissions depending on whether the hybrid buses use air-conditioning. J2711 could be revised to include a test procedure for those who want to test the buses with air-conditioning. FTA sponsored the development of the first version of J2711, which was a successful effort.

Develop a credit system for technologies that provide demonstrated improvements in fuel economy or lower overall energy usage.
Some transit properties noted that, currently, there is no incentive to purchase buses with lower energy use. A few properties thought that it would be beneficial to allow transit properties to accrue credits for deploying higher fuel economy buses; these credits could be applied in state implementation programs.

Bibliography and Further Reading

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Appendix A: Questionnaire

Interview Questions for "Analysis of Electric Drive Technologies For Transit Applications: Battery-Electric, Hybrid-Electric, and Fuel Cells" for the Federal Transit Administration

The Northeast Advanced Vehicle Consortium is conducting an analysis of the current status of electric drive technologies for transit applications. The analysis will cover battery-electric, hybrid-electric and fuel cell buses, although with an emphasis on hybrids. This analysis will examine current transit deployment levels; assess the benefits to transit and the broader community; assess the status of the technology, assess capital, operating and maintenance costs; and explore the barriers to widespread deployment.

The culmination of this analysis will be a report to FTA on the status of electric drive technologies for transit, and recommendations for how FTA could support or advance greater deployment of these technologies.

As part of the research, the NAVC is interviewing industry stakeholders – transit agencies, bus manufacturers, drive system suppliers, engine manufacturers, and interest groups – for their views on electric drive technology for transit buses.

The results of these interviews will form a key part of the analysis.

The report will be primarily for internal use at FTA, but may be made public. All interviewed subjects will be listed in the report, but the report will not reveal any direct quotes from any interviewee.

The NAVC will ask the following questions to all interview subjects, although each interview may cover other issues that the interview subject believes are relevant to the analysis.

- Give your overall impression of electric-powered buses (hybrid, battery or fuel cell).
- For transit agencies, what are your plans for purchasing electric-technology buses, if any?
- What are the drivers for the purchase of electric drive transit buses?
- What do you think are the barriers to the purchase by transit authorities of electric drive buses?

- Specifically with regard to hybrid buses, please provide your view of the main barriers/challenges to widespread commercial deployment:
  - Technical Challenges?
  - Costs?
  - Certification and Testing?
  - Institutional Barriers?
  - Others?

- How are/will the 2007 heavy-duty diesel rules impact the purchase of hybrid transit buses?

- Should and can operating costs and capital costs be combined for one overall number for evaluating and comparing the life cycle costs of different bus technologies?

- Should there be a different definition of "useful life" for new technology just entering the market?

- Are there maintenance and/or training issues with hybrids or other technologies that can be ameliorated by FTA?

- Are there other barriers that you think the FTA should help industry overcome? What can you recommend to FTA to encourage FTA participation in encouraging electric drive bus deployment?