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A Report on Worldwide Hydrogen Bus Demonstrations, 2002-2007

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National Fuel Cell Bus Program

A Report on Worldwide Hydrogen Bus Demonstrations, 2002-2007

March, 2009

Prepared by:
Center for Transportation and the Environment
730 Peachtree Street
Suite 330
Atlanta, GA 30308

Breakthrough Technologies Institute
1100 H Street, NW
Suite 800
Washington, DC 20005

Prepared for:
Federal Transit Administration
Office of Research, Demonstration and Innovation
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, D.C. 20590

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13. ABSTRACT (Maximum 200 words) **Between 2002 and 2007 more than 20 cities in the United States, Europe, China, Japan and Australia have demonstrated buses powered by fuel cells or hydrogen-fueled internal combustion engines, as well as a variety of fueling and related technologies. The project team used a method of in-depth targeted interviews to gather insight from key participants in these hydrogen bus demonstration projects. The resulting report analyzes lessons learned from the demonstrations, identifies key remaining challenges for introduction of the technology, and suggests potential roles for government in supporting commercialization of fuel cell buses.**			
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Foreword

Since 2002, hydrogen-powered buses have been deployed in transit fleets of more than 20 cities around the world. These demonstrations represent a major investment in moving fuel cell and hydrogen transit technologies toward commercialization.

This report summarizes interviews with demonstration participants in North America, Europe, Japan, China and Australia. Interview participants include bus and fuel cell manufacturers, infrastructure suppliers, transit agencies and technology integrators. The report also draws upon technical reviews that have been published about the demonstrations.

Among other things, the report examines the performance and reliability of bus and refueling technologies, describes experiences in the design and permitting of maintenance facilities, and offers recommendations to help move hydrogen buses toward mainstream viability. Transit agencies and other demonstration participants generally had positive experiences with hydrogen-powered buses and expressed a strong desire to continue advancing the technology. This report will be of interest to transit agencies, bus and drivetrain manufacturers, policymakers, and others interested in low and zero-emission mobility options.

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Simon Whitehouse, Independent Consultant
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Interview Participants
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Summary

Transit agencies in the United States, Europe, China, Japan and Australia have recently demonstrated buses powered by fuel cells or hydrogen-fueled internal combustion engines in their fleets, as well as a variety of fueling and related technologies. This report gathers insights from these demonstration participants, analyzes lessons learned, identifies key remaining challenges, and suggests potential roles for government in supporting commercialization.

Most demonstrations reported better than expected performance and strong passenger acceptance. For example:

- the buses performed well across a wide range of operating conditions, including hilly and flat terrain, hot, and cold temperatures, and high and low-speed duty cycles;
- there were no major safety issues over millions of miles of vehicle service and thousands of vehicle fuelings;
- most participants found that drivers preferred fuel cell buses to compressed natural gas (CNG) or diesel, noting their smooth ride, ease of operation, strong acceleration, and ability to maneuver well in traffic;
- several participants noted that fuel cell bus drivers were less tired at the end of their shifts, mainly because the buses produced significantly less noise than diesel or CNG;
- 75% of surveyed passengers reported a quieter ride, and 63% reported a smoother ride, as compared with conventional buses;
- most participants found that the buses were easily incorporated into revenue service, with some accommodation for increased vehicle weight and height and longer fueling times; and
- most participants noted that developing fuel cell bus maintenance facilities was not as challenging as expected. However, because each site developed its own solutions, future research could capture lessons learned and develop best practices and guidelines.

Participants expressed strong enthusiasm for deploying more hydrogen buses, with most indicating a desire for larger fleets, such as 50 – 100 buses per site. Participants noted that the demonstrations successfully incorporated lessons learned from prior demonstrations, thus significantly advancing the technology. The following lessons learned may help ensure the success of future demonstrations:

- successful projects require a strong commitment throughout the transit agency and a highly engaged and committed program manager;
- early and ongoing outreach to the community and local regulators is critical to build support and facilitate the permitting process;
- fuel supply must be properly matched with fuel demand to prevent venting of excess fuel, which lowers overall fuel economy and increases the cost of the program; and
- pooled procurements could help manufacturers understand the potential market, establish standards, and reduce costs. Several participants noted that transit properties are forming "consortia" for sharing information on issues and for joint vehicle procurements, and that these might be a mechanism for other transit properties to consider.

Key challenges to commercialization revealed by the demonstrations were:

- **Vehicle Range.** The most significant challenge was range. Diesel buses typically operate for 18 to 20 hours per day, over a range of about 186-217 miles (300-350 km), using one tank of fuel. At many demonstration sites, fuel cell buses required refueling after about 200 km (93-124

miles). Hybrid fuel cell systems can significantly extend range, and many participants believe that future fuel cell buses will be hybridized.

- **Fuel Cell Durability.** Despite significant progress, fuel cell durability must be substantially increased and/or the cost of replacement fuel cell stacks must be substantially decreased. Most participants expressed confidence that the durability challenge will be solved.

- **Energy Storage.** The batteries on fuel cell hybrid buses did not perform as well as expected. Participants noted that batteries must be improved, and research into other energy storage systems, such as ultracapacitors and flywheels, would be valuable.

- **Bus Components.** Participants reported that a number of fuel cell-related problems were caused by supporting components to the fuel cell. Several felt that these supporting components need additional development to be more robust, to improve lifespan, and to be sufficiently rugged for transit use.

- **Infrastructure Reliability.** Many participants believed that infrastructure technology needs to progress significantly for fuel cell buses to be commercialized. Equipment failures, including nozzles, hoses and compressors, were common and buses were occasionally put out of service for weeks or months. Several participants felt that there was little or no investment being made to solve these challenges.

- **Hydrogen Filling Times.** Currently, hydrogen fast-fills typically range between 10-30 minutes per bus, which is longer than the fueling times for diesel (2.5-10 minutes) and CNG fast-fills (4-7 minutes). As larger bus deployments are planned, the fueling time, which is a function of both the infrastructure equipment and the buses, will need to be reconsidered. Many feel that the fast-fill times will need to be reduced to accommodate more vehicles, or that fueling stations should plan for more pumps. The latter option, however, will require more investment in infrastructure and will increase the fueling stations' footprint.

Demonstration participants envisioned two primary roles for government in future demonstrations: the development of a long-term, rather than project-specific, strategic plan for fuel cell buses and an accompanying funding commitment until commercialization is viable.

Transit operators indicated that government funding will be needed to cover incremental costs of purchasing and operating fuel cell buses through 2015, based on current commercialization timeframes. Many participants believe that government support for larger deployments (50-100 vehicles), and bigger hydrogen bus purchases, will help to bring down bus costs. Several also believe that monetizing carbon emissions could significantly improve the life-cycle cost implications of hydrogen buses.

Participants also suggested that government should invest in hydrogen highways or other linked hydrogen infrastructure, sustainable hydrogen pathways to maximize the environmental benefits of hydrogen buses, standardizing hydrogen safety procedures for transit agencies, disseminating information on codes and standards, and developing certification standards and training curricula for maintenance technicians. Participants also would like government to direct funding for basic research and development to resolve challenges revealed by these demonstrations.

Introduction

Over the past six years, more than 20 cities around the world have, or are currently, demonstrating fuel cell or hydrogen powered buses in their transit fleets. Most demonstrations involve individual cities and transit agencies, but some have been multi-city demonstrations, such as Europe's Clean Urban Transport Europe (CUTE) and HyFLEET:CUTE programs and China's fuel cell bus project.

The purposes of these programs include testing hydrogen buses in differing climates and over long duty cycles, and gathering information to improve the performance of vehicles and fueling infrastructure. Significant progress has already been made in identifying issues and crafting solutions, and new tests, demonstrations, and procurements are being planned.

This report gathers insights from key participants in these demonstrations, such as bus and fuel cell manufacturers, infrastructure suppliers, transit agencies, and technology integrators. These insights will help the industry plan future demonstrations and deployments of hydrogen buses. In reviewing this report, it is important to note that most sites operated three or fewer buses and transit agencies were required to scale investments for relatively small sub fleets. As the number of hydrogen buses grows, the nature and scale of infrastructure and related investments is likely to grow significantly.

Although a few demonstrations used hydrogen internal combustion engines (HICE), most used fuel cells. Fuel cells use an electro-chemical process to convert hydrogen into electricity, with heat and water as the only byproducts. HICE vehicles combust hydrogen in modified internal combustion engines. Hybrid buses combine either a fuel cell or a HICE with a system to capture and store braking energy, thus improving energy efficiency and increasing range. North American and Japanese demonstrations use hybrid buses, while all other demonstrations use non-hybrid buses. The demonstrations therefore offer an opportunity to compare the performance of fuel cell, HICE and hybrid bus technologies, and to assess experiences in planning, implementing, maintaining and refueling the buses.

Methodology

The project team, comprised of Center for Transportation and the Environment (CTE) and the Breakthrough Technologies Institute (BTI), set out to interview key players in the recent generation of global fuel cell bus demonstrations. The goal was to analyze lessons learned, identify key challenges that remain on the pathway toward commercialization, and identify potential roles for government in supporting commercialization.

An expert panel was assembled to guide the project, which included:

- Simon Whitehouse, Independent Consultant
- Leslie Eudy, National Renewable Energy Laboratory
- Monika Kentzler, Daimler
- Ron Harmer, BC Transit
- Paul Scott, ISE Corp.
- Hideaki Akamatsu, Toyota Motor Corporation (retired)
- Michael Tosca, UTC Power
- Jeff Grant, Ballard Power Systems
- Jaimie Levin, AC Transit
- Patrick Schnell, TOTAL

- Rajat Sen, Sentech
- Brian Weeks, Gas Technology Institute

A candidate list of 20 case study sites was compiled from international hydrogen bus demonstrations operating between 2002 through 2008. This included sites where either fuel cell or HICE buses were used in regular transit operations, not just for testing or short deployments. Buses fueled with hydrogen/natural gas blends were excluded.

The list of 20 potential sites was reviewed by our expert panel. The expert panel recommended analyzing 16 projects, because these projects had buses still in operation or had concluded operation no later than 2005. The expert panel also suggested interviewing sites that are planning new demonstrations or deployments as a way to gather insight regarding the impact of previous demonstrations.

An attempt was made to interview each of the selected sites. Interviews could not be scheduled with two sites - Santa Clara, California and Barcelona, Spain - but for the others (Figure 1), contact was made with the program operator (typically either the city or a transit agency), the infrastructure provider, the fuel cell supplier, the bus provider, and the integrator, if different. Most interviews were by telephone, although some chose to provide written responses. To encourage open and frank discussion, interview responses were to remain anonymous. Background on all of the interview participants is available in Appendix 1.

An interview guide was created, based upon the issues the expert panel believed most important. The questions were tailored slightly to the various demonstration partner categories: the fuel cell company, bus company, transit operator, integrator and infrastructure supplier. A sample guide can be found in Appendix 2.

Figure 1. Interview Participants

North America
Fuel cell hybrid buses: AC Transit (Oakland, California); CTTRANSIT (Hartford, Connecticut) ; SunLine Transit Agency (Palm Springs, California)*; BC Transit (British Columbia, Canada)
**SunLine also operates a hydrogen hybrid internal combustion engine (HHICE) bus*

CUTE, ECTOS, STEP and HyFLEET:CUTE
Fuel cell buses: Amsterdam, Netherlands; Beijing, China; Hamburg, Germany; London, UK; Luxembourg; Madrid, Spain; Perth, Australia; Reykjavik, Iceland
Hydrogen internal combustion engine (HICE) buses: Berlin, Germany

Private partners:
Fuel cell manufacturers: Ballard Power Systems, UTC Power
Bus suppliers, integrator: Daimler, ISE Corp., Toyota Motor Corp. (JHFC Bus Demonstration Project)
Infrastructure operators: Shell Hydrogen, TOTAL, Vattenfall Europe

Key Issues and Lessons Learned

The demonstration sites employed a variety of fuel cell, drivetrain, hydrogen fueling, and other related technologies. Although each experienced unique challenges, some conclusions can be applied across all sites:

- The experience with the buses was very positive, with most locations reporting better than expected performance in revenue service and good passenger acceptance.

- Most agencies were pleased with how easily the buses were incorporated into revenue service, but reported having to make some accommodations to their standard operations, primarily due to lower vehicle range, greater vehicle weight and height, longer fueling times, and the lack of standardized hydrogen safety procedures in maintenance facilities.

- Fuel cell stack durability is improving as a result of feedback from ongoing demonstrations, but significant increases in fuel cell lifetime are required to become competitive with diesel and compressed natural gas (CNG) buses.

- Improvements are required for the energy storage component of hybrid buses. The current generation of sodium chloride (NaNiCl) batteries are particularly troublesome.

- Most locations reported that infrastructure reliability was a major concern. For example, many participants indicated that the prototype hydrogen dispensing equipment suffered significant breakdowns, and believed this often was because the equipment had been designed for other fuels. The consensus is that infrastructure must be designed and built specifically for hydrogen.

- It is important to ensure that fuel supply is properly matched with fuel demand. In some locations, excess hydrogen was produced and subsequently vented, significantly lowering overall fuel economy and increasing the cost of the program.

- Experience with maintenance facilities was generally positive, with most sites accommodating the buses with relatively modest investments. However, each site developed its own solutions and there appeared to be significant "reinventing of the wheel." Future research could capture lessons learned and develop best practices and guidelines for maintenance facilities.

- The most successful projects had a strong commitment throughout the transit agency and a highly engaged program manager who was focused on the project and personally committed to the technology.

- Early and ongoing outreach with the community and local regulators is critical to easing public safety concerns and facilitating the permitting process. Drivers and mechanics that are fully engaged with the project can be important fuel cell bus advocates.

The following sections provide more detail about these and other issues.

Fuel cells and batteries

The demonstrations were designed to assess the reliability of the fuel cells and related components in bus revenue service (Table 1), testing the stacks under different climates and duty cycles. Generally, the performance of the fuel cell stacks exceeded expectations, but the batteries and supporting components experienced significant challenges. Table 2 shows the availability rate of buses in the various demonstrations.

Fuel Cells
Many transit agencies were surprised and favorably impressed with the steady progress made in fuel cell reliability. For example, bus availability, an indicator of vehicle reliability, was greater than 90% in the CUTE, Ecological City Transport System (ECTOS), Sustainable Transport Energy Project (STEP) and HyFLEET:CUTE fuel cell bus trials. This was higher than expected.

Fuel cell-hybrid buses, which were deployed in the United States, had a target rate of 85% availability, but experienced lower rates due to a number of issues involving the battery, hybrid drive and fuel cell. Contamination in the cell stack assembly (CSA) caused premature power degradation of the fuel cells, and was reportedly resolved when a new generation of CSAs was installed in the buses.

Participants reported that a number of fuel cell-related problems were caused by supporting components to the fuel cell. Several felt that these supporting components need additional development to be more robust, to improve lifespan, and to be sufficiently rugged for transit use. Problems included software issues, trouble with the cell voltage monitoring board, and inverter issues that forced several upgrades.

Table 1. Fuel Cell and Energy Storage Components			
Bus Model	***Fuel Cell***	***Energy Storage***	***Deployment***
Mercedes Benz Fuel Cell Citaro	Two Ballard Power Systems fuel cell modules, >125 kW gross power each	Non-hybrid system	CUTE, HyFLEET:CUTE, ECTOS, STEP, China Fuel Cell Bus Project
New Flyer H40LFR	Ballard HD6 Fuel Cell Module, 150 kW	Cobasys 576 V - 340 kW NiMH battery system	BC Transit
Toyota-Hino FCHV-BUS2	Toyota Fuel Cell Stack, 180 kW	NiMH secondary battery	Tokyo
Van Hool A330	UTC Power PureMotion 120 fuel cell power system, 120 kW	3 modules, 216 cells, NaNiCl ZEBRA batteries; 53 kWh capacity	AC Transit, SunLine, CTTRANSIT
Wrightbus	Ballard, 75 kW	Ultracapacitor	London

Participants recognized that the durability of fuel cells has grown steadily from generation-to-generation. Fuel cell longevity in the CUTE trials was notably greater than expected - averaging 3,000-3,200 hours, with a minimum longevity of 1,800 hours and a maximum of 5,000 hours.

Warranties offered on the next generation of fuel cell buses, by fuel cell manufacturers UTC Power and Ballard and by integrator ISE, also are growing. UTC Power has indicated that it is extending its fuel cell warranty from 4,000 hours to 6,000 hours, with the potential of reaching 10,000 hours based on performance measures. Ballard is offering a fuel cell warranty of 12,000 hours/five years, an increase over the warranty of 4,500 hours offered during the CUTE bus trials. ISE is now providing bus warranties of 10,000-12,000 operating hours. Several transit operators indicated that availability of longer service warranties is a big step forward.

Many transit agencies stated that fuel cell lifetime needs to grow considerably, because agencies typically operate buses for 10-15 years. One operator recommended that fuel cell buses will need to achieve 30,000 operating hours to be competitive with incumbent technologies. Alternatively, another suggested that the fuel cell stack could be made sufficiently inexpensive to enable cost-effective replacement over the life of the bus, as is currently done with diesel buses, which require two or three engine replacements or rebuilds during a lifetime.

Some participants indicated that standardization of components and materials would be of value and several indicated that the Hydrogen Bus Alliance, an international group working to develop and procure hydrogen fuel cell buses, is currently supporting such an effort.

Batteries

Fuel cell hybrid buses are deployed in North America, at AC Transit and SunLine in California, and CTTRANSIT in Connecticut. These buses use ZEBRA NaNiCl batteries that have performed below expectation, with deployment sites reporting frequent battery system troubles. Several participants felt that battery technology is not advancing.

Battery issues have been caused by state of charge imbalances in battery cells that lead to propulsion system software over-volt errors. The technology companies and integrator have achieved some success in controlling this problem. Battery controller electronics failures have also been an issue and software changes have been made to minimize this problem.

Despite poor battery performance, many participants believed that the next generation of fuel cell vehicles will need some form of hybridization to increase range and fuel efficiency and several indicated that the next generation of fuel cell buses likely will use either lithium-ion (Li-ion) or nickel-metal hydride (NiMH) batteries. Li-ion batteries have been undergoing testing for several years, although it was indicated by one participant that, while promising, these batteries are not yet ready.

It also was suggested that future fuel cell deployments consider a plug-in battery configuration. A plug-in hybrid fuel cell bus trial is planned for Burbank, California during 2009.

Table 2. Availability Rates of Hydrogen Buses

Project	Bus Type	Availability Rate*
CUTE*	Fuel cell	Fleet average >90%
ECTOS*	Fuel cell	~90%
STEP*	Fuel cell	>90%
HyFLEET:CUTE*	Fuel cell	92.6% (includes CUTE figures)
HyFLEET:CUTE*	HICE	92.8%
AC Transit**	Fuel cell hybrid	Aug. 2007 – Jul. 2008: 41%. Downtime primarily due to battery issues. Apr. 2006 – Dec. 2007: 55%. During the first five months availability was 80-90%. Availability later declined due to problems with batteries and fuel cell stack assemblies.
SunLine**	Fuel cell hybrid	Apr. 2008 – Oct. 2008: 85% for six of seven months. For two months, availability was 100%. Availability in Jul. 2008 was low due to hybrid system electrical problems. Battery problems have continued, but are less likely to impact availability. Aug. 2007 – Jul. 2008: 68%. Downtime caused by waiting for a new version of the fuel cell power system to be installed, and problems with the hybrid propulsion system and battery.
SunLine**	HHICE	Jan. 2006 – Mar. 2008: 59%. Downtime primarily due to fan belt breaks causing the engine to overheat, requiring a rebuild, and a subsequent engine fire. Bus was out of service from Jul. 2007 – Mar. 2008.
CTTRANSIT**	Fuel cell hybrid	Aug. 2007 – Jul. 2008: 62%. Downtime caused by waiting for a new version of the fuel cell power system to be installed, and problems with the hybrid propulsion system and battery.

* The CUTE program defines availability as the number of downtime days per month as a proportion of the total number of days the buses were scheduled to be used in that month. CUTE, ECTOS, STEP and HyFLEET:CUTE data obtained from project reports.

** NREL defines availability as the percent of days that the buses are planned for operation compared to the days the buses are actually available. U.S. transit agency data obtained from National Renewable Energy Laboratory (NREL) reports.

Infrastructure

Transit agencies developed individual strategies to meet their hydrogen production and fueling needs. Appendix 3 provides an overview of the infrastructure arrangements made by the demonstration sites interviewed and other sites that made such information publicly available. Figure 2 lists key considerations used by demonstration sites while developing hydrogen fueling stations. Figure 3 discusses one site's plan to increase on-site hydrogen production to accommodate a larger bus fleet. The transit agencies experienced mixed results with hydrogen infrastructure. A number of sites experienced fueling equipment malfunctions that temporarily halted the demonstrations. Many of the interview participants indicated that the fuel cell buses appeared to be farther along the development pathway than infrastructure technology. The consensus was that infrastructure technology needs to progress significantly for fuel cell buses to be commercialized, and the demonstrations provided some valuable lessons that already have been incorporated by industry.

Siting

Some agencies created temporary fueling facilities while others sought to accommodate a permanent hydrogen bus fleet. Challenges included station footprint and capacity for growth, and effective outreach to the nearby community. Key issues were:

Land Availability: A hydrogen refueling station has a larger footprint than a diesel station, mainly because of (1) the need to site the compressor, purifier and other components, (2) the greater volume of hydrogen as compared with diesel per unit of energy, and (3) in some cases, the need for additional dispensers because of the longer fill times for fuel cell buses. For this generation of demonstrations, the number of buses at any one site was low, and thus the station footprint was relatively modest. However, participants noted that as fleet size increases, station size is likely to be a growing concern. Underground hydrogen storage could be considered as stations grow to serve larger fleets.

Community Concern: A hydrogen station can cause concern among local residents and businesses. For example, London chose a site near residential areas and experienced very strong local opposition to the station. This caused lengthy delays, with the station opening months later than had been originally planned. Similarly, despite choosing an industrial location for its station, Perth also experienced strong opposition by neighbors, which was resolved by building a concrete wall around the station. By contrast, Reykjavik's fueling station was located in an industrial area and no public concerns or problems were reported. In general, participants highly recommended early and ongoing public education to raise awareness and build community support and pride in the project.

Figure 2. Key Considerations in Fueling Infrastructure

Siting: community outreach well in advance, footprint of fueling and production equipment, anticipating larger fleets

S*torage capacity:* matching capacity to fleet demand and space availability

Hydrogen supply: on-site production or trucked in from off-site production

Fueling capability: fast-fill vs. slow fill; reliability; backup plans

Fueling responsibility: drivers or maintenance staff, infrastructure staff

Environmental considerations: source of hydrogen production and method of transport to facility

Hydrogen Supply and Storage

We examined hydrogen storage and supply at 21 sites: the 16 sites listed in Figure 1 plus Porto, Stuttgart and Stockholm, which were part of the CUTE program. Of these sites, 10 used on-site production, 10 used hydrogen trucked in from off-site production facilities, and one used both. Of those that produced hydrogen on-site, five produced the hydrogen via electrolysis and five used natural gas reformation. The technologies used for on-site production also varied, with some sites using commercial reformation and electrolyzer technologies, and other sites testing prototype steam reformers.

On-Site Production: On-site production enables hydrogen production to be scaled to demand, avoiding the need for large storage facilities. However, since many on-site production technologies are in the development phase, substantial amounts of hydrogen were often stored as a back-up supply.

Demonstration sites featuring on-site production used either natural gas steam reforming or water electrolysis. In Europe, the CUTE program tested some pre-commercial production technologies. The performance was mixed, with most of the problems occurring with prototype steam reformers. By contrast, another agency has reported good results from its commercial natural gas reformation system.

In general, the demonstrations showed that on-site production can produce hydrogen of comparable quality to off-site production. Some sites noted contaminants in the fuel, such as oil, water, particles, and carbon monoxide, but these contaminants appear to have been introduced through the compressors as part of the fueling process, not the production process.

Figure 3. Planning for Larger Fleets

One transit agency has implemented a modular hydrogen supply system that can offer a solution to the problem of matching hydrogen supply to demand for a fuel cell bus fleet. The agency produces hydrogen on-site to fuel its two hydrogen buses and is able to scale up production to fuel up to five more buses. The agency reports that they also can easily increase production to accommodate 12 to 14 buses by adding another hydrogen reformer unit and can accommodate additional hydrogen storage.

Off-Site Production: Off-site production reduces the complexity of the hydrogen station and avoids equipment reliability concerns surrounding on-site production technologies. However, this method requires substantial storage capacity and may increase the well-to-wheels environmental impact of hydrogen, which must generally be trucked to the station. The use of hydrogen pipelines could reduce the environmental impact of off-site hydrogen production, especially if hydrogen is produced from nearby green resources.

Off-site production also requires careful estimates of the amount of hydrogen required to reduce the need for venting, which seriously impacts fuel efficiency and costs. For example, one station was scaled to produce hydrogen for six buses, but due to vehicle cost only three buses were deployed. Because hydrogen demand was less than planned, 50% of the hydrogen was vented to the atmosphere. Similarly, another agency estimated hydrogen demand based on the assumption that buses would end their shifts with almost empty tanks. However, the buses actually had fuel remaining at the end of their shifts, thus requiring less hydrogen for refueling, which resulted in venting of 60% of the stored hydrogen.

One site used liquid hydrogen storage. Liquid hydrogen converts to a gaseous state at temperatures above -253C ("boil off") and venting is required to prevent over-pressurization of the tank. While boil off and venting cannot be completely eliminated from fueling stations, proper sizing of storage and ensuring that hydrogen supply is well-matched with demand can help minimize fuel loss.

Fueling Capability and Reliability

Hydrogen refueling often takes longer than diesel or CNG, with a typical fill ranging from 8-30 minutes. By contrast, diesel requires 2.5-3 minutes and CNG requires 4-10 minutes. These demonstrations showed progress in fueling optimization, with agencies reporting reduced fill times over the course of the projects.

Some demonstrations found the longer fueling times problematic, while others found ways to accommodate the increased times, such as fueling overnight or adding additional dispensing pumps. As fleets grow larger, however, such accommodations may become increasingly difficult, particularly if they add to station cost and footprint. Thus, further reductions in fueling time - by increasing the fueling speed of buses and/or making improvements to infrastructure fueling technologies - will be a key goal of the next phase of fuel cell bus development. Some of the upcoming bus deployments include a commitment to complete refueling in less than 10 minutes.

Frequent equipment failures were common, especially with the CUTE, STEP, ECTOS, and Santa Clara programs. The main failures involved rupture of the compressor membrane, dispenser hose failures, and leaks at the dispenser or nozzle. As a result of the CUTE program, a major nozzle supplier quickly modified its technology and is working on a new nozzle system. Standardization of refueling nozzles was recommended.

Many participants noted that the poor reliability occurred because many components had been designed for CNG, not hydrogen. Fueling equipment needs to be designed or re-engineered to the specific needs for hydrogen, such as fueling hoses that will operate at extremely low temperatures and materials that will not be subject to embrittlement.

Another critical infrastructure issue was the lack of a widespread supply chain for replacement components. Malfunctioning systems sometimes took a long time to repair, although some transit agencies found that suppliers responded quickly to replace faulty or malfunctioning parts. For many, however, buses were occasionally out of service for weeks, or even months, until fueling station issues were resolved. Santa Clara's fueling operations, however, were less impacted by repairs or maintenance due to the presence of a back up compressor.

Fueling Responsibility
About half of the cities allowed only specialized personnel to fuel the buses, while the other half permitted drivers or maintenance staff to refuel the buses, as they would for conventional vehicles. Some transit agencies noted that safety regulations or, in some cases, union rules, prevented drivers from performing refueling and other operational responsibilities. This issue seems to be more of a "growing pain" that can be resolved as standards are developed and adopted.

Environmental Considerations
Many of the demonstrations focused upon developing reliable fueling strategies rather than upon developing low emission hydrogen pathways, although the CUTE, ECTOS and STEP trials did examine the environmental impacts of the different fueling strategies. To maximize the environmental benefit from adoption of fuel cell buses, many participants stressed that, in the longer term, there is a need to prove economically viable "green" hydrogen pathways, such as electrolysis from renewable sources. Currently, however, electrolysis is expensive and is not suited to producing quantities sufficient for a large bus fleet.

It appears likely that the next stage of bus deployments will continue to focus on reliable hydrogen fueling rather than the most environmentally benign options. In the future, pipelines could supply renewably-generated hydrogen, or it could be produced on-site from renewable sources.

Vehicle integration

In the CUTE, ECTOS and STEP bus trials, the Original Equipment Manufacturer (OEM) integrated the completed drive train into the vehicle during the production process, working in close partnership with the fuel cell and drive train manufacturers. However, in the U.S. OEMs do not currently have the knowledge to integrate the fuel cell propulsion system into buses. Several participants felt that the OEMs' knowledge base must be increased to become more involved in integration and to be able to handle subsequent system diagnostics. OEMs should be encouraged to begin integrating fuel cells as they would on a normal bus. It was felt that having fewer parties involved in the production process would make the process less complicated.

For example, one U.S. participant indicated that many small things were wrong with their bus and believed that this was due, in part, to several companies being responsible for bus production. Another stated that when transit agencies order a bus they want to specify it directly from an OEM, not a technology company, and felt that production must to move from one-off projects to commercially available vehicles. In the next phase of bus trials they expect production will be improved, since one entity will be responsible for the bus.

Vehicle operation

Operating schedules varied by site, with some starting off slowly (for 6-8 hours per day) then increasing to 16 or more hours per day, six or seven days a week. Some sites limited the buses primarily on one or two transit routes, while others deployed them on a variety of routes, varying the time of operation, range and difficulty. Figure 4 discusses one operator's implementation strategy.

Overall, the buses performed well across a wide range of operating conditions, including hilly and flat terrain, hot, and cold temperatures, and high and low-speed duty cycles. Moreover, most agencies found that drivers preferred fuel cell buses to CNG or diesel, noting their smooth ride, ease of operation, strong acceleration, and ability to maneuver well in traffic. One agency noted that drivers were less tired at the end of their shifts because of the reduced noise of the fuel cell bus and quieter passenger conversations.

The most significant operational challenge was range. Diesel buses typically operate for 18-20 hours per day using one tank of fuel. At many demonstration sites, however, fuel cell buses needed to return to the depot after 7-8 hours for refueling. While three agencies felt that the range of the vehicles was acceptable, nine found the range to be too short, with three of the nine having expected it to be greater. One transit agency noted that, based upon their previous experience with CNG, they had expected a shorter range for hydrogen buses. Many participants believed that hybrid systems will significantly extend range by improving fuel economy, with one participant noting that hybrid technology should increase the range to near 250 mi (400 km), comparable to diesel buses.

Figure 4. Case Study: Integrating Fuel Cell Buses Into Operations

One agency isolated the fuel cell project into a single division, which allowed fine tuning of day-to-day activities. This also enabled:

- learning specific to the fuel cell bus, including managing block assignments, maintenance schedules, and data recording; and
- the ability to deploy the best and most interested technicians and drivers to the project.

Another strategy was to hold regular, weekly meetings with coalition partners. These meetings included, among others, representatives from maintenance, procurement, training, operations, and marketing.

Some expressed concern about the increased height, weight and higher center of gravity of the fuel cell buses, which is comparable to the configuration of CNG buses. These impacted operations at several agencies and forced careful consideration of routes due to underpass height and weight limitation on bridges. In another case, a speed restriction was implemented due to concerns about the higher center of gravity. Several agencies mentioned that the next generation of buses will address these concerns by lowering height and center of gravity, and using lighter materials in buses to reduce weight.

Generally, fuel economy was considered to be good but fuel efficiency needs improvement. Fuel wasted during idling and by air conditioning and heaters was a concern at some sites. Other sites noted that efficiency varied significantly by driver and duty cycle.

Finally, one of the colder sites experienced problems with excess spinning of the drive wheels in snow and ice. It was anticipated that this problem will be corrected by improving traction control.

Maintenance

Although good standards exist for the use of hydrogen in industrial settings, there are currently no standards for the use of hydrogen in transport maintenance facilities. Transit agencies generally needed to determine how to handle hydrogen safely in enclosed facilities, which often included nearby bays servicing high voltage systems and buses fueled by other liquid and gaseous fuels. Some transport agencies noted that previous experience in permitting CNG, together with established relationships with regulators, made it easier to permit hydrogen. Most participants noted that early and frequent communication with local regulators is extremely important during this process. It was suggested that standards for hydrogen in maintenance facilities are needed to speed up the process even more.

Hydrogen buses have unique requirements that must be accounted for in maintenance facilities. The main facility requirements relate to the following features:

- Safety: Facilities that garage or service fuel cell buses must be equipped to detect hydrogen leaks and to prevent the possibility of an electrical spark igniting any leaked hydrogen.
- Height: The fuel cell buses in these demonstrations generally are 18-25 inches (46-64 centimeters) taller than typical transit buses.
- Access for maintenance: All demonstration buses have hydrogen storage on the roof. The Daimler/ Ballard buses also locate the fuel cells on the roof.

Generally operators addressed these issues with different strategies based upon:

- type of existing facilities, i.e., facility size, capacity and dimensions and whether it served diesel, CNG and/or electric-hybrid buses;
- local regulations and relationships with local safety officials. This is an important factor since regulations vary widely; and
- agency/operator's safety philosophy.

Figure 5. Common Features of Maintenance Facilities

- *Roof-level access:* Installation of gantries and hoists to enable access to rooftop equipment. Safety protection (e.g. harnesses) for workers.
- *Hydrogen sensors and alarms:* Sensors need to be installed along the roof above the bus, because hydrogen is lighter than air.
- *Ventilation:* Sufficient ventilation must be provided to ensure that hydrogen concentrations remain at safe levels.
- *Spark Prevention.* Many agencies installed explosion proof lighting while others placed plastic covers over the lights. Tools and equipment should be anti-static.
- *Hydrogen release pipes:* The storage tanks on the CUTE buses were equipped with pressure relief valves. In case these failed, "hydrogen release pipes" were attached to the high pressure line, prior to maintenance, to safely vent hydrogen

Although each agency chose a slightly different strategy, certain modifications were common to all sites and are likely to be standard for fuel cell bus operations. These are shown in Figure 5. Appendix 4 provides a chart showing facility arrangements made by the demonstration sites interviewed, as well as for others that did not participate in the interviews but have made such information publicly available.

One important issue is the fill status of the storage tanks when a bus is pulled into its maintenance bay. Some demonstration sites vent hydrogen to partially depressurize tanks before entering the facility, thus effectively lowering vehicle fuel economy. For example, one site reduced pressure to 600 psi prior to entering the maintenance garage. By contrast, another built a new facility specifically for fuel cell buses, enabling the buses to enter the garage without venting. As shown by Table 3, most demonstrations modified existing maintenance facilities rather than constructing purpose-built facilities. Figure 6 describes one transit agency's low-cost approach to workshop modification.

There are three key findings from the interviews with operators about their experience with garaging the fuel cell buses.

- First, a clear majority of participants noted that implementing fuel cell bus maintenance facilities was not as challenging as they had expected.
- Second, given the wide range of approaches to maintenance facilities, additional research to establish best practices and guidelines would be very useful.
- Third, as hydrogen bus fleets expand and the volume of hydrogen increases, maintenance facilities will be a bigger issue. For example, larger fleets likely will require purpose-built facilities rather than modified and shared existing facilities. Both BC Transit and CTTRANSIT are building new garages for their next deployments of over three vehicles.

Figure 6. Case Study: Low-Cost Approach to Maintenance Facility Modification

CTTRANSIT spent $75,000 to modify an existing bus facility. The existing garage had good air flow, with the inside air being changed seven times an hour. Additional steps included:

- Directing ceiling-mounted ductwork toward the bus.
- Installing a fan on the bus bay ceiling.
- Installing five hydrogen detectors over the bus.
- Installing plastic covers over existing light to keep hydrogen away from the fixture.

Buses are operated in the garage on battery power and hydrogen is purged if work is conducted that may cause a spark. Approvals from local fire and safety officials were received in nine months. A new garage is being built, using similar design concepts, for a new fleet of fuel cell buses.

Table 3. Facility Modification or New Construction

Agency	Number and type of buses	Facility: Modified or New?
AC Transit	3 hybrid fuel cell buses	Modified diesel bus facility bay for 2 buses
Amsterdam	3 fuel cell buses	Modified
Barcelona	3 fuel cell buses	New for hydrogen and CNG
BC Transit	20 hybrid FCBs	Modifying Victoria facility for 3-4 buses
		Build new Whistler facility for all
Berlin	15 HICE buses	Modified
Beijing	3 fuel cell buses	New
CTTRANSIT	1 hybrid fuel cell bus	Modified
Hamburg	3 to 8 FCBs	New - converted existing structure used for other purposes
London	3 fuel cell buses	New facility
Luxembourg	3 fuel cell buses	Modified
Madrid	3 fuel cell buses	Modified
Perth	3 fuel cell buses	Modified bay for 3 buses
Porto	3 fuel cell buses	New - converted existing structure used for other purposes
Reykjavik	3 fuel cell buses	Modified
Santa Clara VTA	3 fuel cell buses	New separate 2-bay facility designed and built for fuel cell buses
Stockholm	3 fuel cell buses	Modified
Stuttgart	3 fuel cell buses	Modified
SunLine	1 hybrid fuel cell bus	Existing outdoor hydrogen facility

Safety

A majority of participants noted that one of the top positive outcomes was the absence of any major safety problems. This is confirmed by the published data, which shows very few significant safety incidents over millions of miles of vehicle service and thousands of vehicle fuelings. Participants also noted that the demonstrations promoted future deployments by identifying and resolving potential safety issues, establishing safety procedures, raising public awareness and comfort, and familiarizing local officials with hydrogen. Table 4 provides an overview of the safety records of the major fuel cell bus demonstration projects.

The CUTE and HyFLEET:CUTE program provides a particularly good example of using early demonstrations to understand and resolve safety issues. Incidents that occurred in one city would quickly be reported to the other partner cities, and a secure website was established that allowed participants to exchange information.

Table 4. Reported Safety Incidents

Program/Project	Safety Record
CUTE, ECTOS, STEP – 11 cities	No major safety incidents Approximately 100 minor safety incidents
AC Transit	No major safety incidents
CTTRANSIT	No major safety incidents
Santa Clara VTA	Safety incidents early in project: • Liquid hydrogen leak ignited during commissioning of hydrogen station • Several minor incidents of excessive venting or leaks • Multiple "false alarms"
SunLine	No major safety incidents

The experience of working with local officials to approve maintenance facilities and refueling stations varied widely. Local fire and safety officials are still largely unfamiliar with the use of hydrogen in transit and so few cities have established hydrogen codes and standards for these facilities. For example, for the CUTE project, three cities took less than nine months to secure approval for their fueling stations; three took ten to twelve months; one took 24 months; and one took more than 30 months. Two were able to use existing CNG standards, enabling approval in six months. One received approval in four months because the program was treated as a demonstration, not a permanent installation.

At several sites where regulations did not exist, transit agencies performed their own research to determine what measures were needed to ensure safety of their maintenance facilities. They educated the regulators and were successful in obtaining approval for the facilities.

A few sites encountered local resistance. One site took over 30 months to secure approvals due to neighborhood opposition, and the station was decommissioned following completion of the demonstration. Another site built its fueling station behind a concrete barrier largely because of community concern.

Finally, in the early part of its demonstration, Santa Clara VTA found that its extensive safety mechanisms resulted in multiple false alarms. For each false alarm, the hydrogen fueling station would shut down and the local fire department was dispatched, resulting in significant downtime for the buses and an unnecessary use of fire department resources. This experience highlights the need to balance legitimate safety issues with the risk of negative impact upon service and the resources of safety agencies. VTA successfully resolved this issue and experienced no further problems as the demonstration progressed.

Education

Staff Training
Some sites were very inclusive in their training, offering a "Hydrogen 101" to all personnel. These courses generally covered system basics and safety for the bus, maintenance bay and fueling station. Participants recommended that education begin well in advance and that education continue throughout the project. Among other things, this helps to ensure "buy-in" to the project by all levels of staff, from the CEO down. Training, ensuring constant communication, and assembling and maintaining a good project team was critical to many agencies in addressing day-to-day operations and to ensuring project success.

Driver Training
Drivers were very positive about operating hydrogen buses and many were impressed with the vehicles' performance. Many participants stated that drivers "liked" or "loved" the buses and that "they enjoyed driving the vehicles". Others mentioned that the vehicles had good acceleration, and a quiet and smooth ride. Figure 7 discusses in greater detail the main factors influencing driver acceptance.

Drivers required minimal additional training to operate fuel cell buses. Generally, transit agencies expanded their standard "new bus" training with a lesson on operating and trouble-shooting the fuel cell system. In addition, drivers received the same basic safety training that agencies provided for maintenance personnel and any other agency staff in contact with the buses.

Most transit agencies designated a subset of drivers for the fuel cell and HICE fleets. Several participants reported that having a select fleet of fuel cell bus drivers was an important factor in the success of their demonstrations. This is because drivers generally were selected for their ability to communicate about fuel cell technology and hydrogen safety. This is an important consideration for agencies implementing fuel cell buses, since these buses and their drivers act as "ambassadors" for hydrogen and fuel cells to the wider community. Moreover, the selected drivers were often cultivated to be champions of the projects among their colleagues within the agency.

Figure 7. Main Factors Regarding Driver Acceptance

A significant positive finding from all sites was that drivers liked the hydrogen vehicles, and a majority found that their drivers enjoyed driving the fuel cell buses more than conventional buses. The main reasons cited for the high level of driver acceptance include:

- *Improved acceleration.* Drivers liked the continuous torque and smooth acceleration of the electric drivetrain.
- *Positive feedback from riders and the public.* Drivers liked the status of driving "special" buses and the attention riders and the public gave to the vehicles. They also enjoyed driving to special events and answering questions about the buses.
- *Reduced noise.* Drivers appreciated the reduced noise and some reported feeling less tired at the end of their shift.

A few participants indicated the importance of selecting a group of drivers committed to the hydrogen demonstration program. The demonstrations are important tools for gathering data on bus performance, and improper treatment of the bus could hinder the process. As a result, most demonstrations encouraged drivers to treat the buses like any other bus.

Mechanic Training
Because these demonstrations involved pre-commercial buses, the demonstration sites had substantial technical support from the technology providers. The CUTE, ECTOS and STEP sites each had a technician from Ballard and Daimler on-site throughout the demonstrations. Similarly, UTC Power and

ISE Corporation provided on-site staff support for SunLine and AC Transit. The on-site support ensured that problems could be addressed quickly and that the technology providers could control access to their intellectual property.

Transit agencies typically designated several senior mechanics to observe the work performed by the on-site engineers provided by the technology companies. Selecting a few top mechanics helped create champions within the agency for the bus and enabled the mechanics to better understand the buses. At several sites, where engineers were not available on a full-time basis, or had departed after a two-year deployment, agency maintenance crews successfully took over maintenance and simple diagnostic duties for the vehicles. At another site, two mechanics took over all maintenance and repair of the buses after the OEM technician left, including maintenance and repair of the fuel cell. One site chose not to deploy in-house mechanics to observe the engineers, but in hindsight would recommend it.

Training of First Responders

Early and ongoing training of first responders was recommended to make personnel familiar with pressurized gas and hydrogen. Several transit agencies developed training videos for fire departments and have offered video and in-person staged hydrogen emergency efforts. Another developed a "cut sheet" that shows first responders where they cannot cut because of high voltage electrical lines and pressurized hydrogen lines.

Public acceptance

Descriptions of public reaction included "enthusiastic", "much better than expected", "widespread excitement and acceptance", and that the public "appreciates the initiative", "likes clean air projects" and "wants more". In many cities the buses were identified by special branding and people would smile and wave when the buses passed. Others flagged down the buses to ask questions.

All transit agencies used the buses for special demonstrations, rides and events, and many received third-party requests for such events. One agency offered a monthly "open day" where the public could ride the buses for free, tour the hydrogen filling station, and attend presentations and discussion about the buses. In general, the "touch, feel, ride" approach was a common mechanism for public communication.

Several agencies stressed the need to prepare the public well in advance, beginning outreach long before the buses arrive. The public's knowledge and acceptance of hydrogen should be increased by educating them about the technology and safety measures that will be in place. Many transit agencies mounted a media campaign that included outlets such as television, radio, and newspaper, as well as producing project brochures and discussing the project at public meetings. Early and ongoing public communication about the project was highly recommended by the participants and is critical to success in the projects.

Several transit agencies extended their efforts to assist in developing educational curricula. Two transit agencies helped in devising a hydrogen education program for local schools, including a visit by schoolchildren to see the hydrogen buses. This effort proved fruitful - a survey of 12-to-15 year-olds in one of these cities found that the youth recommended the use of more fuel cell buses to make the city greener. One of the agencies also helped a local university to develop hydrogen courses.

Rider response

In demonstrations around the world, riders and the public have had positive experiences with the fuel cell bus demonstrations in their local municipalities. When surveyed about their general opinions of their local demonstrations, between 85% and 93% of respondents felt positively about the demonstration. Table 5 shows a summary of responses to key issues surveyed by recent demonstration projects.

Concerns about the environment play a large role in respondents' support for hydrogen fuel technology across demonstration sites. In Beijing, 88% of respondents cited environmental concerns as the major reason for supporting hydrogen-fueled vehicles, and the environment was also the number one reason cited by respondents to the AcceptH2 surveys. The CTTRANSIT survey found that of the 66 respondents who would prefer hydrogen buses to conventional ones, and over one fifth (21%) cited environmental concerns as their justification. At AC Transit, 91% of those surveyed believed it is important to develop alternatives to petroleum.

Overall, respondents expressed positive experiences with the comfort level of the fuel cell buses. At CTTRANSIT, 84% of riders surveyed preferred the fuel cell bus to conventional buses. CTTRANSIT survey participants cited improved noise level (90%) and improved smoothness of ride (89%) over conventional buses. In the Toyota survey, quietness was the most often cited positive comfort experience (53%) followed by smoothness of ride (23%). In Berlin, improvement in exhaust received the highest positive marks on a scale of 1 to 5 (4.2) and in Luxembourg decreased vibrations received the highest marks (3.92). The majority of AC Transit survey respondents, 75%, experienced a quieter ride on the fuel cell buses and 63% experienced a smoother ride.

Awareness of the demonstrations in the AcceptH2 project ranged from 20% in London to 59% in Luxembourg. In CT Transit's survey, 62% were aware that fuel cell vehicles are zero emission and 58% were unaware that the fuel cell bus has a fuel economy double that of conventional buses. At CTTRANSIT 81% or respondents said riding the bus improved their opinion of the technology. The AcceptH2 study found that experience with the buses did not improve the acceptability of the technology.

Where hydrogen bus demonstrations are being performed, the public appreciates both the direct personal improvements that hydrogen buses provide, such as comfort of the ride, and the indirect benefits of the buses, such as decreased negative environmental effects. In Iceland, 37% of respondents are willing to pay more to support the large-scale introduction of hydrogen buses and participants in the AcceptH2 project are willing to pay an average of €0.37 ($0.50 USD) above regular fare to support hydrogen introduction. There is strong public support for the demonstration projects and, in general, the public supports expansion of the programs on larger scales.

The following is a review of passenger surveys previously conducted at demonstration sites around the world.

Table 5. Rate of response to key issues involved in fuel cell bus demonstrations						
Issue	**ECTOS**	**AcceptH2**	**Toyota**	**Beijing**	**CTTRANSIT**	**AC Transit**
Have positive opinion of local demonstration	93%	90%	Not surveyed	Not surveyed	Not surveyed	85%
Environmental concerns are major reason for supporting hydrogen technology	Not surveyed	Yes	23% believe the bus to have positive environmental effects	88%	18%	91% believe it is important to develop alternatives to petroleum
Awareness of buses	47% occasionally notice bus; 18% notice often	Aware of their city's demonstration: Perth: 59%; Luxembourg: 51%; Berlin: 45%; London: 20%	Not surveyed	Not surveyed	66% aware they were on a fuel cell bus	75% aware they were on a fuel cell bus
Support large-scale introduction of fuel cell buses	86% support replacing oil with hydrogen	67% unconditional; 23% conditional	Not surveyed	Not surveyed	Not surveyed	81%
Find the fuel cell bus to be quieter than conventional	Not surveyed	Not surveyed	53%	Not surveyed	90%	75%
Find the fuel cell bus to be smoother than conventional	Not surveyed	Not surveyed	23%	Not surveyed	89%	63%

ECTOS
In Reykjavik, Iceland in March 2004, 200 ten-question, assisted surveys were conducted on fuel cell buses (50), on diesel buses (50), near bus stops (50), and with neighbors living near main routes (50). The results of the survey were presented in 2004 in *ECTOS:Assessment and Evaluation of Socio-economic Factors*. The majority of respondents, 93%, commented positively about the demonstration (60% were "very positive" and 33% were "positive"). Additionally, the majority of respondents, 86%, had positive attitudes towards the development of hydrogen as a fuel for buses, cars and other vehicles.

Over a third of respondents, 37%, indicated that they would be willing to pay more for hydrogen than for diesel during the early phases of introduction. However, 28% of respondents want hydrogen to be less expensive than standard fuel during introduction. Nearly half of respondents, 49%, believe hydrogen to be safe, and 50% of respondents were unsure of the safety of hydrogen.

Almost half of the respondents, 46%, would like to see more public relations work done regarding the buses. The buses have a fairly high profile on the street with 47% of respondents claiming to notice the buses on the road once in a while and 18% noticing the buses often. Respondents were given the option of including their own comments at the end of the survey. Many of the comments surrounded respondents desire to learn more about how hydrogen is produced, and when to expect the commercialization of the technology.

AcceptH2

The 2005 *AcceptH2 Full Analysis Report* presents the results of a survey-based study conducted in London, Luxembourg, Berlin and Perth. The study involved the surveying of hydrogen and conventional fuel bus users and non-bus users both pre- and post- introduction of the fuel cell buses.

Awareness of the hydrogen bus trials ranged across the four cities. In Perth, 59% of respondents were aware of the trials, in Luxembourg, 51% of the respondents were aware, 45% of Berlin respondents were aware, and only 20% of London respondents were aware. The survey found that attitudes towards hydrogen technology were largely positive. When asked if they thought that the demonstrations were a good idea, 90% of participants responded positively overall in both the pre- and post-bus-introduction surveys largely citing environmental concerns. When participants in the post-bus-introduction survey were asked about their level of support for large-scale introduction of buses in their city, 67% offered unconditional support and 23% noted factors on which their support for the introduction would depend.

The survey also contained contingent valuation questions that asked participants about their willingness to pay more for large-scale introduction of hydrogen buses in their city. Of those willing to pay more, €0.37 ($0.50 USD) was the average amount above current fare they were willing to pay.

A portion of the surveys in Berlin and Luxembourg asked hydrogen bus riders to rank their experiences with the hydrogen buses' appearance, comfort, vibrations, tailpipe emissions and noise on a scale of 1-5, with 5 being excellent. Berlin riders ranked their experience with the buses' improved exhaust highest at 4.2 while Luxembourg riders ranked vibrations highest at 3.9. Berlin riders ranked the hydrogen buses higher overall.

This survey study found that experience with a hydrogen bus did not increase acceptability of the technology. Additionally, this survey found that environmental concerns appear to play a large role in unconditional support for hydrogen technology.

Japan Hydrogen & Fuel Cell Demonstration Project

Surveys were distributed at bus stops with 272 returned by mail for a response rate of 58%. When asked how they felt about the fuel cell bus, 53% of respondents found the bus quiet and 23% found the bus smooth. About one quarter of respondents, 23%, believed the bus to have positive environmental effects.

China Fuel Cell Bus Project

Rider surveys were conducted both pre- and post- fuel cell bus introduction at several bus stops as well as on board buses intermittently. In the first survey, 55% of the public was aware of what a fuel cell bus was and post-introduction, 70% of respondents were aware. Safety and cost issues were the greatest concerns to respondents. However, the numbers of respondents who did not worry about safety increased significantly from 35% pre-demonstration to 88% after the buses were introduced. When asked what they enjoyed about the fuel cell buses, 88% of respondents cited their environmental friendly nature, 44% cited quietness, and 29% cited comfort.

CTTRANSIT

CTTRANSIT conducted a one-day survey effort on its fuel cell bus on August 27, 2008. The survey was handed out to fuel cell bus riders by their marketing department with 79 surveys completed representing an estimated response rate of 80% for the number of passengers who rode during the survey time.

When they boarded the bus, 66% were aware that it was a hydrogen-fueled bus. It was the first time riding the fuel cell bus for 82% of respondents, but 15% had ridden on it occasionally and 1% has ridden it often. Riders were then questioned on their knowledge of fuel cell bus technology. When asked if they were aware that fuel cell buses have zero emissions, 37% of riders responded yes. Similarly, 34% were aware that the fuel cell bus has double fuel economy compared to a standard diesel bus, and 32% were aware that the electric motors charge the batteries when the bus is braking. Nearly half of the respondents, 48%, were aware that the buses utilize an electric hybrid drive system.

The majority of respondents enjoyed the comfort level of the fuel cell bus with 90% of respondents indicating that the fuel cell buses noise level was better than a standard diesel. Additionally, 82% of respondents felt that the hydrogen bus' acceleration was better than a standard diesel. When asked about smoothness of ride, 89% felt that the fuel cell bus' level of vibration was better than a standard diesel. When asked to compare the bus' temperature control aspects, 61% felt that the hydrogen bus heating was better than a standard bus and 67% felt that the air conditioning was better on the fuel cell bus.

The majority of respondents, 84%, preferred to ride in a hydrogen bus to a standard diesel. When asked why they preferred a hydrogen bus, 14 respondents explicitly mentioned benefits to the environment, clean air, or less pollution. 10 respondents specified seating or better comfort as their reason for preferring the hydrogen bus.

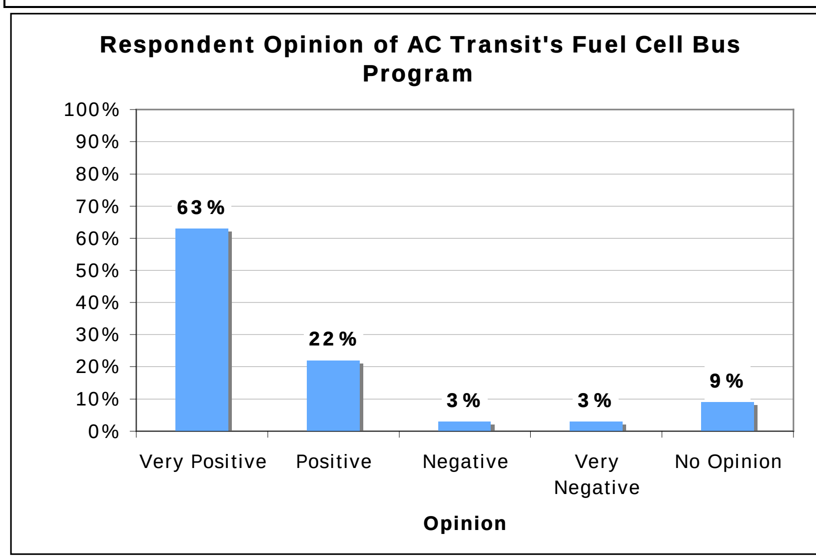
Riding the hydrogen bus improved the majority of riders' opinions of fuel cell technology (81%). Aspects beyond rider comforts such as zero emissions, enhanced the rider experience for 28% of respondents, although 35% reported that these additional characteristics do not enhance their experience.

AC Transit

As part of this research effort, CTE worked with AC Transit to design, distribute, and analyze a rider survey for AC Transit passengers. A copy of the survey is provided in Appendix 5. The research team placed the surveys on the fleet's three fuel cell buses to be self-administered from September 17, 2008 to October 31, 2008. Upon completion, the surveys could either be left in a return box on the bus or returned by mail. Four hundred ninety-three surveys were returned. The survey results show that the majority of AC Transit bus riders had an extremely positive opinion of the fuel cell bus demonstration.

Three quarters of respondents were aware that they were riding on an alternatively fueled bus when they boarded. When asked of their opinion of the fuel cell bus demonstration, the majority of riders, 85%, responded positively about the demonstration. Only 6% of respondents had "negative" or "very negative" opinions about the demonstration. Figure 8 shows the distribution of these responses.

Figure 8. Passenger Opinion of AC Transit's Fuel Cell Bus Program



Rider survey respondents also wrote in comments elaborating on their opinion of the fuel cell bus program. There were 191 written comments of which 72% were positive, 16% were negative, and 12% were neutral. Of the positive responses, the majority, 48%, related to environmental issues and included such comments as "no harmful emissions", "less smog", "it shows that we can be green now". Of the positive comments, 12% were in support of energy independence and included such comments as, "it is a scientific approach to solve the energy crises", and "it is wonderful to see public transit working on alternative fuels". The remaining 38% of positive responses were general comments such as, "it's a great idea", and "keep doing it!"

The majority of negative comments had nothing to do with the bus' fuel cell propulsion system and rather focused on issues of comfort and seating design. Of the negative comments 87% centered on the raised height of some seats and those seats' inaccessibility for elderly and disabled passengers. There were 23 general comments/questions of which eight were requests for more information, six were questions regarding life-cycle costs, four were cost concerns and only one was a safety concern. The remaining four general comments were in regard to general transit service concerns.

Two survey questions asked riders to compare the comfort levels between fuel cell buses and conventional buses. More than 75% of respondents experienced a quieter ride on the fuel cell bus compared to the conventional bus and 63% experienced a smoother ride on the fuel cell bus.

When asked how AC Transit's use of fuel cell buses affected their opinion of the transit agency, 64% of respondents reported an improved opinion and 30% of respondents reported no change. The majority of respondents, 70%, also reported improved opinions of their city because of the fuel cell bus demonstration. The large majority of respondents, 91%, believed it is important to consider alternatives to petroleum. When asked to consider replacing all buses with fuel cell buses, 81% supported expansion of AC Transit's fuel cell bus program.

There were also 279 written-in comments at the end of the survey. Of these comments, 51% were positive, 17% were negative and 32% were neutral questions or concerns. The majority of positive comments, 85%, were general praise and support for the program such as, "very good, thank you" and "the sooner, the better". The other 15% of positive comments were focused on environmental, health, and energy independence issues.

Of the negative comments, 89% were in reference to interior design, seating, and the bus' chassis, not the fuel cell propulsion system. There were also 89 written neutral concerns that included issues such as cost (19%), life cycle concerns (16%), requests for more information (7%), and safety (5%). Twenty-nine of the written concerns related to general transit issues such as the level of driver service, fare cost, and bus timeliness.

The respondents' comments indicate a strong level of support among bus riders for AC Transit's fuel cell bus program. The majority of comments were positive in nature and reveal riders' good direct experiences with the fuel cell buses as well as their general support for development of the technology. When targeting markets to increase support of the program, the agency should focus on environmental issues as these green concerns have a strong influence over riders' positive support of fuel cell buses. Additional focus should be put on the fuel cell technology's ability to decrease dependence on fossil fuels.

Public relations campaigns will also benefit by focusing on the technology's life-cycle costs. Survey respondents displayed a significant level of life-cycle awareness and voiced clear concerns about how hydrogen is produced and where the energy for production originates. Respondents' basic cost concerns centered on increased fares, and cost comparisons of fuel cell to hybrid and other alternative fuel technology.

Management and partners

The participants noted that a strong commitment throughout the transit agency - from the CEO down to line staff - was important to the projects' success. They believed that the most successful demonstrations had a proactive program manager who was focused on the project and personally committed to the technology. One participant observed that agencies with a pro-fuel cell, proactive manager, as well as buy-in throughout the agency, achieved the best project outcomes.

Many participants also noted that choosing the right technology partners and maintaining strong relationships and communication is critical. One agency held, without fail, weekly, one-hour conference calls that included all technology partners and internal representatives from maintenance, procurement, training, operations, and marketing.

Several participants found that multi-city programs, such as CUTE and HyFLEET:CUTE, provided valuable opportunities for information sharing and learning. These cities shared information quickly enabling partner cities to take lessons learned and address issues as needed.

The role of HICE buses

The participants' opinion of HICE and hydrogen hybrid internal combustion engine (HHICE) technologies varied from strongly supportive, to strongly opposed. A majority, however, believe that these technologies are not viable long-term options. Several participants suggested that they may serve a role as a bridge technology to fuel cell vehicles, helping in the development of a larger hydrogen infrastructure. A few were taking a wait-and-watch stance, looking for reduced cost and improved performance and reliability.

A number of issues have been raised regarding the vehicles, most notably the problems with engine life and reliability being experienced during this phase of vehicle development. Many participants pointed out that HICE and HHICE buses are expensive to purchase and maintain and do not offer the reduced noise, zero emissions, and fuel efficiency benefits of fuel cell buses, yet face the same technical challenges of dealing with hydrogen fuel. Operating range of HICE buses is also limited, requiring buses to be refueled mid-day. However supporters pointed out that fuel economy and range are improved through hybridization. Another supporter indicated that catalytic converter technology could also be used to reduce emissions, making the exhaust "virtually identical to that of a fuel cell".

A number of participants also noted that development of HICE and HHICE technology could divert resources away from fuel cell development, with some suggesting that they are a "step backward." One noted that "In general the automobile industry is heading towards electric propulsion systems. There is a synergy between hybrid-electrics and fuel cell development, but there is no synergy with HICE." This is because hybrid buses are becoming a larger market share and this will help to bring components, such as inverters, electric engines and batteries, to market, further facilitating the ongoing development of fuel cell and fuel cell hybrid vehicles.

Nonetheless, those supportive of HICE and HHICE buses argue that these technologies will be available sooner, and at a lower price, than fuel cell buses. Another suggested that HICE and HHICE buses could become an "end game" technology if performance issues are resolved. However, about half of participants argue that these buses offer no advantages over fuel cell buses.

The next phase of hydrogen bus demonstrations

All of the transit agencies interviewed for this project expressed enthusiasm for deploying more hydrogen buses, with most indicating a desire to implement larger fleets, not just a handful of demonstration models. While these agencies are a self-selected group with an interest in clean technologies, this enthusiasm is a testament to their experience with fuel cell buses in daily transit operations.

The biggest barrier to future fuel cell bus procurements cited by the interview participants is the vehicle cost. As a consequence, in the next phase of fuel cell bus commercialization deployments will continue to be driven largely by government policies and support. Table 6 lists confirmed demonstration projects or procurements of hydrogen buses. As the table shows, most agencies that are planning further deployments are doing so with government funding. Of those in our interviews who did not have new deployment plans, most cited the inadequate government funding to offset the higher vehicle cost as the primary reason. A few agencies reported that government funding was being used to support less expensive clean bus alternatives, such as CNG, liquefied petroleum gas (LPG) and HICE.

These planned projects also reveal that industry and governments have not settled on a single approach to moving fuel cell buses forward on the commercialization pathway. A few sites are focused on larger deployments of full-size transit buses using next generation fuel cell systems. These are intended to build on the knowledge base derived from the recent smaller-scale demonstration projects and allow greater understanding of how fuel cell buses will operate in real-world fleet operations. At the same time, the industry will be developing single prototypes intended to address the remaining technical and cost barriers to fuel cell commercialization by demonstrating new fuel cell bus integration concepts. Many interview participants felt that more low-level demonstrations would not offer real value to the industry, and that the larger-scale deployments are the preferred strategy for this next phase of development. This issue is discussed further in the section on the role of government.

Finally, participants mentioned three main categories of collaborative activities that could be valuable for future demonstrations.

- *Information sharing*. Several participants suggested the need for a centralized forum for information sharing, given that knowledge about such issues as maintenance and infrastructure relating to hydrogen is not widespread. The Hydrogen Bus Alliance was most often cited by participants as offering value in this regard. The Federal Transit Administration (FTA) National Fuel Cell Bus Working Group and Workshops also serve as a vehicle for information sharing among members.
- *Pooled procurements*. The participants indicated that pooled procurements could help manufacturers understand the potential market, establish standards, and reduce costs. A few participants mentioned the Clinton Climate Initiative as a mechanism for achieving pooled procurements. Several noted that transit properties are forming "consortia" for sharing information on issues and for joint vehicle procurements, and that these might be a mechanism for other transit properties to consider.
- *More regional collaboration*. Finally, some cited the value of certain regional collaborative activities, such as the California Fuel Cell Partnership; CALSTART, which is working to create a transit user group; the Japan Hydrogen and Fuel Cell Demonstration Project; and the California Hydrogen Highway. In particular, some participants indicated that greater collaborations with hydrogen suppliers should be a key focus.

Table 6. Next Phase of Demonstrations and Procurements		
Customer/City	**Planned Demonstrations or Procurements**	**Delivery**
AC Transit and partners, California	Purchase eight 40-ft fuel cell buses, with an option for 12 more from Van Hool, using UTC Power fuel cell stacks and battery TBD. *Compliance with CARB Transit Fleet rule.*	2009 to 2010
City of Burbank, California	Demonstrate one 35-ft battery-dominant fuel cell bus from Proterra. *Funded by CARB*	2009
San Francisco MTA California	Demonstrate one 40-ft battery-dominant bus with fuel cell APU. Drive system by BAE systems and Hydrogenics. *Project of the FTA National Fuel Cell Bus Program*	2010
SunLine Palm Springs, California	Demonstrate one 40-ft fuel cell bus with New Flyer chassis, UTC Power fuel cell and ISE integration. *Project of the FTA National Fuel Cell Bus Program* Demonstrate 30-ft Thor bus with Ballard fuel and Li-ion batteries. *Funded by CARB, ACMD and FTA*	2010 2008/2008
CTTRANSIT Hartford, Connecticut	Demonstrate up to four 40-ft fuel cell buses with UTC Power stacks, and one 35-ft battery-dominant plug-in fuel cell bus supplied by Proterra with Hydrogenics fuel cells. *Projects of the Federal Transit Administration (FTA) National Fuel Cell Bus Program* Demonstrate one additional fuel cell bus. *Supported by federal funding*	2009
MassPort Boston, Massachusetts	Demonstrate one fuel cell bus with Nuvera fuel cell and ISE integration. *Project of the FTA National Fuel Cell Bus Program*	2010
New York State	Demonstrate one composite fuel cell hybrid bus with lithium ion (Li-ion) batteries, supplied by GE Systems. *Project of the FTA National Fuel Cell Bus Program*	2010
New York State	Demonstrate two fuel cell buses. *Project of the FTA National Fuel Cell Bus Program*	2010
BC Transit	Purchase 20 40-ft fuel cell buses supplied by New Flyer with Ballard fuel cell stacks and Cobasys NiMH batteries. *Supported by federal and provincial governments*	2010
Amsterdam, Netherlands	Purchase two fuel cell buses.	2010
GVB, Amsterdam, Netherlands and Regional Verkehr Köln, Cologne, Germany	Purchase four articulated Phileas fuel cell buses using Nedstack fuel cells, two for each city. *Project of Germany's NIP program (managed by NOW)*	2010
Hamburg, Germany	Demonstrate 10 fuel cell buses. Will construct fueling station capable of supplying 1,000 kg/day to support up to 20 buses and a few cars. *Project of Germany's NIP program (managed by NOW)*	2009
North Rhine Westphalia, Germany	Purchase three 5.3 meter fuel cell buses from Hydrogenics. *Funded through Germany's NRW program and EU*	2009
Transport for London London, England	Demonstrate five fuel cell buses. Fuel cell bus supplier is ISE Corporation which is offering a 12,000-hour warranty and will use UTC Power fuel cell stacks. London will build a new hydrogen filling station. *Funding commitment through London Mayor*.	2010
Zaragoza, Spain	Purchase three 5.3 meter fuel cell buses from Hydrogenics.	2008-2009
Sao Paolo, Brazil	Demonstrate five 40-ft Marcopolo buses with Ballard fuel cell stack. *Project of the UNDP Global Environment Fund*	2009
Shanghai, China	Purchase three to six fuel cell buses. *Project of the UNDP Global Environment Fund*	2009-2010

Key challenges to commercialization revealed by the demonstrations

Cost
Hydrogen bus purchases require government assistance to help offset incremental costs greater than those for standard buses. Most participants believe that the cost issue will be resolved as the technologies move toward commercialization. A major factor will be bigger demonstrations and deployments by transit agencies (50-100 vehicles) and larger hydrogen bus purchases. For example, in a March 2006 presentation to the California Air Resources Board, UTC indicated that aggregate orders of at least 100 buses will drive capital cost to competitive levels of around $1 million per bus.

One transit agency noted that a premium of several hundred thousand dollars per bus might make fuel cell buses attractive for limited purchases, while another felt that a premium of $100,000 or less would make it possible for every bus in the fleet to be a fuel cell-powered. Participants noted that the impact of the premium for fuel cell buses will vary significantly, depending upon the extent to which air quality regulations will increasingly require zero-emission buses.

Similarly, participants recognized that additional volume will help reduce the cost to build hydrogen fueling stations, which currently runs about $2 million to $5 million per station. Many participants also suggested that the infrastructure industry needs a pathway, such as an industry roadmap, for installing and expanding new hydrogen infrastructure and for optimizing the stations for larger demand. Companies will be unwilling to invest in hydrogen fueling infrastructure unless a clear market is seen.

Finally, many participants felt that the cost of hydrogen fuel would drop once larger volumes are attained. To further improve the economics, better planning is needed to minimize venting of stored liquid hydrogen, which could be attained by better matching supply with anticipated demand, with more consistent and increased use of the station, and through the development of new storage technologies.

Infrastructure reliability
The next most important challenge is to improve the reliability of refueling infrastructure. As discussed above, equipment failures were common and buses were occasionally put out of service for weeks or months. Participants suggested that larger scale deployments may require redundant systems and an increased supply of spare parts. Participants also suggested that engineering challenges need to be solved, including designing components specifically for hydrogen applications and improving production and storage. Several participants felt that there was little or no investment being made to solve these challenges.

Vehicle Range
European participants operating non-hybridized hydrogen buses indicated that range was not comparable to other buses, which are typically deployed for 18-20 hours at a time over a range of about 300-350 km (186-217 miles). To be able to complete a full shift, the fuel cell and HICE vehicles were operated on split shifts, traveling 150-200 km (93-124 miles), returning to the depot to be refueled, then operated another 150-200 km.

HICE and fuel cell vehicles can attain increased range through improvements in stack and system efficiency and through hybridization, which improves fuel economy. Hybrid fuel cell vehicles employed in North America are capable of operating about 250 miles (400 km), while hybrid fuel cell buses being deployed soon in British Columbia are expected to attain a range of more than 500 miles (800 km). Two agencies mentioned that range could also be extended by using liquid hydrogen, permitting more energy to be stored in a given volume as compared with compressed gas.

Energy Storage
To achieve widescale hybridization, better energy storage is required. This indicates that better battery technology are required, but also suggests more research is needed into ultracapacitors and flywheels to help boost battery performance and reliability. As discussed above, the current generation of batteries performed poorly and significant improvements are needed.

Fuel Cell Durability
Despite significant progress, fuel cell durability must be substantially increased and/or the cost of replacement fuel cell stacks must be substantially decreased. Most participants expressed confidence, however, that the durability challenge will be solved.

Better Components
Components need to be better designed specifically to work with hydrogen systems. As discussed above, many infrastructure components had been validated for other applications, but not hydrogen systems. As a result, there were many infrastructure component failures among the hydrogen fueling sites. In addition, several participants recommended that the next generation of bus components be developed and tested according to automotive standards. Finally, it was suggested that increased standardization industry-wide will be important to commercialization, enabling mechanics to easily replace one component with another.

Hydrogen Filling Times
Hydrogen fast-fills typically take 10-30 minutes per bus, which is significantly longer than the fueling times for diesel (2.5-3 minutes) and CNG (4-7 minutes). As larger bus deployments are planned, the hydrogen refueling process will need to be reconsidered. Many feel that the fast-fill times will need to be reduced to accommodate more vehicles, or that fueling stations should plan for more pumps. The latter option, however, will require more investment in infrastructure and will increase the fueling stations' footprint.

Sustainable Hydrogen Pathways
Several participants suggested that current hydrogen production facilities are insufficient to serve more than 20 or so buses. A viable hydrogen production pathway is needed to support the deployment of larger bus fleets of 50-100 hydrogen-fueled vehicles.

Moreover, many transit agencies would like to use hydrogen derived from a low carbon source. Governments can help spur development and implementation of renewable hydrogen production though implementation of greenhouse gas regulations, participation in emissions trading schemes and through green procurement.

Maintenance Facility Guidelines and Standards
Many transit agencies experienced challenges to enable hydrogen buses to be serviced within indoor workshops, while others had very little difficulty. In part, this is because no protocol or standards exist for hydrogen vehicles in transit workshops. Some agencies were able to modify existing facilities while others constructed purpose-built facilities. For existing buildings, the main issues were venting, leak detection, and spark prevention. Several suggested that it would be helpful if nationwide standards were developed – similar to those for CNG – on how to install and approve hydrogen facilities.

Ability to Maintain Fuel Cell Buses
Many participants felt that transit agency technicians should be prepared to perform regular maintenance on buses and to resolve and repair less difficult diagnostic problems in-house. Mechanics can be taught to read failure codes and key replacement components can be kept onsite, bolstered by a regular spare parts delivery system. Several agencies have also indicated that they would like their own mechanics to take over preventive maintenance of the fuel cell system, if the fuel cell manufacturers will permit more access to the systems.

Several transit agencies felt that preparations should begin now for a future fuel cell bus workforce. Certification standards and training curricula should be developed and approved.

Enhanced Role for OEMs
Several U.S. participants want OEMs to increase their knowledge base to be able to integrate fuel cells during the bus production process. Another suggested that OEMs should also learn to handle subsequent system diagnostics and problem-solving. One U.S. participant indicated that many small things were wrong with their bus and believed that this was, in part, because several companies were responsible for bus production. Another indicated that transit agencies want to specify a bus directly from an OEM and felt that production must move from one-off projects to commercially available vehicles.

Participants in Europe, however, did not express this concern since they worked with a bus producer that performed integration of completed fuel cell drive trains into buses during the production process.

Extend Demonstration Programs
Most participants felt that the fuel cell bus trials should be extended to produce additional data and technological improvements, as well as to build public acceptance. Moreover, participants believed that investments should be strategically concentrated among projects that demonstrate strong local commitment and the ability to leverage resources. Most participants believe, however, that funding for additional demonstrations will be a major challenge. To maximize efficiency, participants suggested building upon the existing bus trials, building up the infrastructure and supporting larger deployments.

Role of government in accelerating commercialization

Demonstration participants envisioned two main roles for government in future demonstrations: the development of a long-term strategic plan for fuel cell buses and an accompanying funding commitment until commercialization is viable, which is expected by 2013-2015. Generally, transit operators indicated that they could not commit to purchasing additional buses without government funding.

Moreover, participants believe that government should provide long-term support, rather than merely funding short-term projects. Without long-term support linked to a policy framework, it was generally believed that further substantial progress will be difficult.

Most suggested that government should focus funding on covering incremental costs of purchasing and operating fuel cell buses. Some also suggested funding for basic research and development to resolve some of the technical challenges revealed by these demonstrations.

Participants also believed that the next generation of demonstrations should be large-scale deployments of 50 or more buses. Many felt that demonstrating fewer than ten buses would simply be repeating what has already been done, rather than moving the technology forward.

A number of participants recommended that future government support be targeted to cities with previous demonstration experience, enabling them to continue building knowledge and leverage prior investments, especially in infrastructure. This concept could be described as the "Centers of Excellence" strategy, described in greater detail in Figure 9.

Participants also stressed the need for a long term-policy framework that supports the demonstration and deployment of fuel cell buses. Participants felt government should invest in:

- long-term planning and strategies for bus deployments, such as a national hydrogen bus roadmap
- hydrogen highways or other linked hydrogen infrastructure
- standardizing hydrogen safety procedures for transit agencies
- disseminating information on codes and standards.
- improved hydrogen production methods that use more renewable energy.

Figure 9. Centers of Excellence

Many participants urged government funding be targeted to a few cities or sites in each region that have successfully demonstrated fuel cell and hydrogen activity. These sites have a team in place, demonstrated partner commitments and the resources necessary to conduct a successful program.

One described a Centers of Excellence strategy, where one or two sites per region would form a "nucleus" to develop hydrogen technology, continually improving it, collecting data, and disseminating results to the larger industry. These site deployments could then grow to form a larger network.

In the U.S., investments could be geographically focused, based in the Northeast, South, Midwest, and West, corresponding with existing programs in these regions. Each region could have one or two Centers of Excellence initially, and over time these "nodes" would connect with new Centers to create a larger network. Another strategy being pursued internationally is the hydrogen highway, such as those being implemented in British Columbia, Canada, and in Scandinavia and Germany (Figure 10).

Participants also suggested that government should establish greenhouse gas reduction mandates, a cap and trade system, and/or a carbon tax. Many noted that monetizing carbon emissions could significantly improve the life-cycle cost implications of hydrogen and fuel cells. Some suggested that, when air quality and carbon costs are included in life cycle cost comparisons, fuel cell buses are comparable to incumbent technologies. Many participants also urged stronger government enforcement of greenhouse gas emissions reductions targets.

Figure 10. Germany's commitment to hydrogen

Between now and 2015, the German government plans to commit €500 million ($658 million USD) to hydrogen and fuel cell development through the National Hydrogen and Fuel Cell Technology Innovation Programme (NIP), working in partnership with industry. Initially, investments will focus upon Berlin and Hamburg, two cities with existing hydrogen infrastructure and experience deploying fuel cell technologies. This will be gradually extended both nationally and internationally. For example, the Scandinavian Hydrogen Highway is being developed in Germany, Sweden and Denmark, with hydrogen stations located roughly 124 mi les (200 km) apart. The goal is to create a hydrogen highway similar to that in British Columbia and California.

Abbreviations and Acronyms

BTI	Breakthrough Technologies Institute
CNG	compressed natural gas
CSA	cell stack assembly
CTE	Center for Transportation and the Environment
CUTE	Clean Urban Transport for Europe
DOE	U.S. Department of Energy
dge	diesel gallon equivalent
ECTOS	Ecological City Transport System
FTA	Federal Transit Administration
gge	gasoline gallon equivalent
HHICE	hydrogen hybrid internal combustion engine
HICE	hydrogen internal combustion engine
JHFC	Japan Hydrogen and Fuel Cell Demonstration Project
kg	kilogram
km	kilometer
Li-ion	lithium-ion
LPG	Liquefied petroleum gas
NaNiCl	sodium nickel chloride
NiMH	nickel-metal hydride
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
PAFC	phosphoric acid fuel cell
PEM	proton exchange membrane
STEP	Sustainable Transport Energy Project

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Appendix 1. Background on Interviewed Demonstration Sites and Project Partners

Appendix 1 provides a review of previously reported activities and outcomes at interviewed demonstration sites and with related project partners. For a complete listing of all fuel cell bus deployments worldwide to date see http://www.fuelcells.org/info/charts/buses.pdf

North American Transit Agencies

Four US transit agencies have hosted fuel cell bus demonstration projects in the period covered by this report: AC Transit in Oakland, California; Santa Clara VTA in San Jose, California; SunLine in Palm Springs, California; and CTTRANSIT in Hartford, Connecticut. These projects have been evaluated by NREL for the U.S. Department of Energy (DOE) and the FTA. This Appendix also includes information on the planned fuel cell bus deployment at BC Transit in Whistler, British Columbia.

AC Transit

Alameda-Contra Costa Transit District (AC Transit) of Oakland, California began a trial of three fuel cell hybrid buses in March 2006. NREL has issued three evaluation reports on the demonstration. The most recent report examines results and experiences between April 2006 and December 2007 and was published in July 2008.

The buses use a 40-ft chassis from Belgian bus company Van Hool, and are equipped with UTC Power's PureMotion 120 kW fuel cell power system integrated into ISE Corporation's hybrid electric drive system in series configuration. The energy storage system consists of three ZEBRA NaNiCl batteries operated in parallel with a total capacity of 53 kW. The batteries are charged overnight. Each bus cost about $3.2 million.

AC Transit fuel cell hybrid bus. Photo courtesy of AC Transit.

AC Transit modified its East Oakland Division facility to contain the fuel cell bus maintenance area. The space can service two buses at once and is separated from the rest of the building by a firewall. The upgrades to this facility cost about $1.5 million.

AC Transit partnered with Chevron Technology Ventures to design and construct a refueling station at the East Oakland facility. The station uses on-site reformation. Natural gas from a utility line is fed into two steam reformers capable of producing a total of 150 kg of hydrogen/day. Total storage capacity at the station is 366 kg. One of the steam reformers is a prototype being evaluated by Chevron to further refine production methods and increase efficiency. Chevron is responsible for the station operation and maintenance, although AC Transit is working on certification of its employees so they can perform bus fueling.

The three buses accumulated 62,191 miles, and 5,765 fuel cell hours, between April 2006 and December 2007. The average fuel economy was 6.23 miles/diesel gallon equivalent (dge), 68% higher than the baseline diesel buses. Twelve percent of total dispensed hydrogen was vented from the bus during the demonstration period in order to allow the vehicle to enter the maintenance facility.

The fuel cell buses attained 80-90% service availability for the first five months of operation, but dropped to 60% availability due to problems with ZEBRA battery failures, early degradation of the fuel cells, and early problems with the air conditioning units. New and upgraded fuel cell stack assemblies have been installed in the buses and are expected to be more durable than the earlier version.

AC Transit has assigned addition mechanics for fuel cell bus maintenance, as the agency plans to increase operations of the existing bus and is planning for a larger fuel cell bus fleet.

SunLine Transit Agency

In January 2006, SunLine Transit Agency, of Palm Springs, California, began demonstrating a fuel cell hybrid bus identical to the three operated by AC Transit. This demonstration offers the opportunity to test the bus in a desert environment. SunLine is also evaluating a $1.2 million HHICE bus with the same electric hybrid drive system as the fuel cell bus, but featuring a Ford Triton engine customized to operate on hydrogen fuel and ultra capacitors for energy storage. NREL's fourth evaluation of SunLine's hydrogen buses was published in January 2009, reporting deployment experiences from April 2008 through October 2008.

SunLine fuel cell hybrid bus. Photo courtesy of SunLine.

SunLine HHICE bus. Photo courtesy of SunLine.

Hydrogen is produced on site by a HyRadix natural gas reformer; this is a commercial product introduced in 2006. Natural gas is piped into the station, and can be reformed at a rate of up to 9 kg of hydrogen/hour. The station can store up to 180 kg of hydrogen. During the latest evaluation period, an average of 27.4 kg/day was dispensed. SunLine's station is also available for fueling by the public.

SunLine constructed a special maintenance facility of aluminum walls and canvas roof with hydrogen sensors for a cost of $50,000. Initially, UTC Power and ISE had technicians available on for daily support. A SunLine mechanic would accompany the UTC and ISE technicians when repairs were made, and the SunLine mechanics have since begun to take greater responsibility for maintenance.

The fuel cell and HHICE buses are being evaluated against SunLine's CNG fleet. Over the course of an earlier 27 month evaluation period (January 2006 - March 2008), the fuel cell bus accumulated 50,931 miles and 3,918 fuel cell system hours, and the HHICE accumulated 42,523 miles. Fuel economy of the fuel cell buses has averaged 8.19 mi/dge, while the HHICE bus has averaged 3.37 mi/dge. The baseline CNG buses' mileage is 3.37 mi/dge.

The same significant fuel cell bus issues as noted at AC Transit were also reported by SunLine including trouble with the ZEBRA battery, air conditioning, and fuel stack decay. As a result, the fuel cell bus availability was 66%. As with the AC Transit buses, the fuel cell was replaced in April 2008 with an upgraded fuel cell power system that has not shown any indication of the early power degradation of the previous version. According the recent NREL report, the bus has operated 11,461 miles and 885 hours using the new fuel cell power system. In total, the fuel cell hybrid bus has accumulated 63,797 miles and 4,912 total operating hours.

The HHICE bus was out of service for most of the period between July 2007 and March 2008. The vehicle experienced two fan belt breakages and overheating experiences followed by an engine fire. The engine was rebuilt with better instrumentation by ISE.

CTTRANSIT

Connecticut Transit (CTTRANSIT) in Hartford began its deployment of one fuel cell hybrid bus in April 2007. The bus design was leveraged from an earlier procurement of four fuel cell buses used by AC Transit and SunLine in California (see above), a 40-ft Van Hool bus with UTC Power 120 kW proton exchange membrane (PEM) fuel cell system and a 53 kWh capacity ZEBRA NaNiCl batteries (three traction batteries operated in parallel). The bus purchase price was $2.4 million, less than the $3.2 million paid for the AC Transit and SunLine Transit buses.

CTTRANSIT fuel cell hybrid bus. Photo courtesy of CTTRANSIT.

The battery is plugged into the battery charger station each night, requiring 4 to 4.5 hours for a full charge. The batteries are kept at a state of charge between 50-60% while the bus is operating to allow energy regeneration from braking back into the batteries.

The CTTRANSIT project enables this bus to be tested in cold weather and a hot, humid summertime climate. NREL conducted a preliminary evaluation of the bus service from April 2007 to June 2008. During this time, the fuel cell bus accumulated 12,115 miles and fuel cell system was operated for 2,049 hours. Issues encountered during this phase of the trial include quality control during bus integration, problems with the battery, heating and air conditioning systems, propulsion system difficulties while operating on icy or snowy surfaces, limited maximum operating speed, and fuel cell power degradation.

CTTRANSIT made minor, low cost modifications to its maintenance facility to permit the bus to be able to operate the bus within the workshop, using battery power only with the hydrogen fuel turned off while operating in the building. Hydrogen fueling took place at UTC Power's hydrogen station located seven miles from the bus workshop, using hydrogen produced by chemical process at Niagara Falls that is delivered to the station.

The agency has found integration of the fuel cell bus into existing operation has been "exceptionally easy." The bus operates on the agency's free Star shuttle/downtown circulator route and in revenue service on CTTRANSIT local routes on weekends. CTTRANSIT plans to implement two additional fuel cell bus projects that will be evaluated under the FTA's National Fuel Cell Bus Program.

BC Transit

BC Transit, the provincial crown agency that provides planning, marketing, fleet and funding support for all transit systems in British Columbia, outside the Greater Vancouver region, will deploy a fleet of 20 fuel cell buses into regular operational service in the town of Whistler during 2009. The 41-foot buses, from Winnipeg bus manufacturer New Flyer, will feature an ISE ThunderVolt hybrid electric drive system, a Cobasys NiMH battery for energy storage, and a 130 kW heavy duty fuel cell module made by British Columbia fuel cell manufacturer, Ballard Power Systems. The fuel cell fleet will be used to showcase Canadian technology at the 2010 Olympic and Paralympic Winter Games in Whistler. The first of BC Transit's fleet of fuel cell buses will undergo testing and evaluation in Victoria during 2008. The buses will have a range of 500 km (311 miles), a top speed of 90 km/h (56 mph) and a life expectancy of 20 years.

Hydrogen fueling infrastructure will be designed and operated by Air Liquide, Sacre-Davey Group, Hydrogen Technology and Energy Corporation and Hydrogenics Corporation. Two fueling stations will be constructed, the first located in Victoria at BC Transit's Langford Transit Centre during 2008, and the second located at a new BC Transit facility in Whistler that will be completed by mid-2009.

International projects

The demonstration projects described in this section were part of a coordinated global trial of hydrogen fuel cell vehicles taking place between 2003 and 2009 (CUTE, ECTOS, STEP, HyFLEET:CUTE). The projects aim to demonstrate emission-free transport systems that in the long term will reduce global greenhouse effect, improve local air quality, conserve fossil fuels, increase public knowledge and acceptance of fuel cell technology, and support development of regulatory infrastructure for the technology.

All of the participating sites included in these global trials (with the exception of Berlin) have demonstrated a limited series of fuel cell-powered Mercedes Benz Citaro buses. The buses are equipped with Ballard's HY-205 P5-1 drive train designed around two Mk9 PEM fuel cell stacks. Compressed hydrogen is stored in nine Dynetek cylinders mounted on the vehicle roof, with a storage capacity of 44 kg of hydrogen at 350 bar, for a range of 200-300 km (124-186 miles).

City	CUTE	HyFLEET:CUTE
Amsterdam, Netherlands	√	√
Barcelona, Spain	√	√
Beijing, China		√
Berlin, Germany		√
Hamburg, Germany	√	√
London, United Kingdom	√	√
Luxembourg	√	√
Madrid, Spain	√	√
Perth, Australia	√ (STEP)	√
Porto, Portugal	√	
Reykjavik, Iceland	√ (ECTOS)	√
Stockholm, Sweden	√	
Stuttgart, Germany	√	

The Berlin site is demonstrating 14 hydrogen internal combustion engine buses developed by MAN Neoman.

CUTE

The Clean Urban Transport for Europe (CUTE) program, which took place between 2003 and 2005, included 27 fuel cell buses operating in nine European cities: Amsterdam, Barcelona, Hamburg, London, Luxembourg, Madrid, Porto, Stockholm and Stuttgart. Two other projects were allied with the CUTE trials and utilized the same vehicle and mirrored the CUTE activities – ECTOS, which took place in Reykjavik, Iceland, and STEP in Perth, Australia. These trials are reported separately, below.

The CUTE buses performed well across a range of topographic and climatic conditions. Fuel efficiency decreased when temperatures were above 18C or below 0C due to conditioning of the bus cabin. Buses on routes with challenging downhill topography also had greater fuel consumption as did routes with slower average speeds. Buses carrying greater passenger loads also had significantly less fuel efficiency.

Bus availability was greater than 90%. Acceleration and drive train performance was comparable to diesel buses. Lifetime and maturity of the fuel cell stacks was better than expected.

Refueling stations were constructed for each of the partner transit fleets and a variety of hydrogen production, compression and dispensing techniques was demonstrated at the sites:

- Hydrogen was generated onsite via electrolysis at Amsterdam, Barcelona, Hamburg, and Stockholm. The units are capable of operating at 25%-100% capacity.
- Hydrogen was generated on site via steam reforming of natural gas at Madrid and Stuttgart. The reformers offer a production capacity of 60 Nm3/h. The Madrid unit had a modular capacity that allowed for future add-on modules. The plant was designed for automatic operation, including automatic start-up, shut-down and load adjustment, using a remote control system.
- An external supply of hydrogen was delivered to Luxembourg (gaseous hydrogen), Porto (gaseous hydrogen) and London (initially gaseous and later liquid hydrogen). Typical liquid hydrogen trucks can carry 3.3 metric tons, or 36,700 Nm^3, enough for a 20-day supply. London began using liquid hydrogen in May 2005. All CUTE cities were able to use an external gaseous hydrogen supply if needed.

The refueling process at all of the cities' stations usually took around 15 minutes with a maximum time of 30 minutes. Overall, 192,000 kg of hydrogen was dispensed in 8,900 refuelings. Over 120,000 kg was produced on-site, with 56% of this coming from green sources.

All stations were operable for more than 80% of the time, with five stations demonstrating availability greater than 90%. Issues with hydrogen compressors caused almost 50% of unavailability across all station units. The second most critical component involved in station unavailability was the dispenser, but down time associated with the dispenser was caused by safety concerns, not actual failure.

At the reformer sites, thermal efficiency was low at 35%, down from an expected 60%. It is believed this was caused by the facility operating at only 50% capacity. For example, the London Hornchurch station had daily withdrawals of 60 kg, much lower than the expected 120 kg/day withdrawal, resulting in substantial boil-off and venting (69% loss). Sites that operated with little or no problems had low hydrogen purging rates of 5% and 10%.

Mercedes-Benz Citaro fuel cell bus used in the CUTE program. Photo courtesy of Daimler.

The CUTE project used the transparent Plan-Do-Check-Act (PDCA) quality management tool to assess differences between expectations and actual performance. One high level improvement that occurred through this methodology was the modification of the nozzle coupling. Local improvements were also made involving dispenser systems, compressors, and on-site production. Daimler and Ballard used the PDCA approach during the planning and operation of the buses and the stations also used this approach, though not as uniformly as for the buses. However, this improved when the Task Force for Safety and Security implemented a common incident and follow-up system. More than 60 incidents were reported using this system.

In 2006, the CUTE program was expanded into the new HyFLEET:CUTE project to continue testing of the current buses.

ECTOS

Icelandic New Energy Ltd. (INE), a private company, coordinated the ECTOS project which deployed three fuel cell buses between 2003 and 2005 in Reykjavik, Iceland. The project was funded by a €3.8 million ($4.86 million) grant from the European Commission. Demonstrations were continued through the HyFLEET:CUTE project during 2006-2007.


ECTOS project fuel cell bus. Photo courtesy of Icelandic New Energy.

The three buses had a total of 5,216 operating hours and traveled 89,243 kilometers (55,777 miles). Bus availability was 90%.

The project's hydrogen fueling station was built alongside a conventional gasoline station. Norsk Hydro Electrolysers (NHE) supplied all equipment to produce, compress and store (at 440 bars) the hydrogen. Over the course of the project, 17,342 kg of hydrogen was supplied.

In August 2004, an incident occurred that resulted in closure of the station for three months. During station startup, an electrolyzer pipe gave way and pressure dropped in the unit. The causes were found to be a level transmitter malfunction, improper manual override of the control system during startup, and a missing demister. A task force was formed that led to implementation of a crisis management plan, an emergency response plan and an incident reporting system.

STEP

STEP demonstrated three fuel cell buses in Perth, Western Australia from 2004-2006. The project was extended into 2007 under the HyFLEET:CUTE program.

The bus operations were focused on three city routes on a regular schedule. As the trial progressed buses were operated on several different routes, but the focus remained on the three main routes. During the trial the vehicles traveled approximately 258,000 km, consumed over 46 tons of hydrogen and carried over 320,000 passengers.

The buses operated an average of 15 days/month for an average of 6.6 hours/day. The average distance traveled on each operating day was 151 km (94 miles). Bus availability was 90%.

The fueling station was designed by Linde AG and was owned and maintained by BP for the first two years of the project. The station could refuel one bus in 12 minutes, a second bus in 14 minutes, and after a 41 minute pause, a third bus within 14 minutes. Hydrogen was derived as a by-product from petroleum refining and was trucked over a distance of 66 km (41 miles) by BP.

Failures at the hydrogen station contributed to a high proportion of time that the buses were out of service. Necessary modifications and repairs included:

- Upgrade to a 700 bar rated hose
- Installation of anti-whip devices to reduce the stress on the hose at its connection points
- Installation of a venting system to reduce the pressure in the hose from 350 bar to 50 bar at the end of the refueling process, between fills
- Additional filters
- Changes to the control system software

The STEP program was funded by the Governments of Western Australia and Australia, and did not receive funding from the European Commission. The program was continued under the global umbrella program HyFLEET:CUTE in 2006.

HyFLEET:CUTE

Daimler fuel cell bus fleet in Hamburg. Photo courtesy of Daimler.

Following the success of the CUTE program, the European Commission initiated the four-year (2006-2009) HyFLEET:CUTE program to build on the CUTE project's successes and to complete new objectives. HyFLEET:CUTE continues demonstrations at many CUTE sites, further testing the buses' durability and, in some cases, pushing then to perform harder. HyFLEET:CUTE will also be testing a new generation of lighter, more efficient fuel cell buses. In all, the project includes 33 hydrogen fuel cell-powered buses being operated in nine cities around the world - Amsterdam, Barcelona, Beijing, Hamburg, London, Luxembourg, Madrid, Perth and Reykjavik.

As of March 2008, the fuel cell vehicles had traveled more than two million km and operated for 133,360 service hours. Bus availability has been 92.6% (this figure incorporates CUTE availability numbers).

In addition, the HyFLEET:CUTE project adds a demonstration of 14 HICE buses in Berlin. These vehicles employ 4-stroke, 6-cylinder engines and were developed by MAN. Four of the buses are equipped with a naturally aspirated Otto engine with a maximum output of 150 kW. Ten buses are powered by a new and more efficient 200 kW lean burn engine with exhaust gas turbo charging and intercooling.

The Berlin filling station, constructed by TOTAL, dispenses liquid and gaseous hydrogen and is capable of fueling 20 buses or 200 private cars. The gaseous hydrogen is produced onsite via a LPG reformer, while liquid hydrogen is trucked in and stored onsite before use. In the future the station will also employ a new generation compressor that uses ionic liquids rather than pistons and two stationary fuel cell systems to use surplus hydrogen to generate heat and electricity for the station.

As of March 2008, the HICE vehicles have traveled 180.000 km over 13,500 service hours, with an availability of 92.8%

China Fuel Cell Bus Project

Citaro bus being fueled at BP hydrogen fueling station in Beijing. Photo courtesy of Daimler.

China's Ministry of Science and Technology (MOST), along with the Global Environmental Facility (GEF) and the United Nations Development program (UNDP), launched a project in 2003 to demonstrate fuel cell buses and hydrogen fueling infrastructure in Beijing and Shanghai. The project is a part of the global HyFLEET:CUTE hydrogen bus demonstration project.

Three Mercedes-Benz Citaro fuel cell buses, similar to the fuel cell buses deployed under the CUTE programs, were demonstrated along a public bus line between 2005 and

2007. The buses' average availability was 89% and average hydrogen consumption was 18 kg/100 km (3.47 miles/gge). Fuel cell system durability averaged 50% lower than at other CUTE demonstration sites. A new maintenance and repair workshop was constructed for the fuel cell buses, featuring hydrogen and other safety-related facilities and automatic emergency safety measures.

A hydrogen fueling station was developed by Beijing SinoHytec Limited, BP and Beijing Tongfang Co. Ltd., using hydrogen generated off-site by natural gas reforming. Fueling capacity is 165 kg/day, with hydrogen available at 250 and 350 bar. Maximum fueling flow is 10 kg/minute. In Phase II, hydrogen will be generated by electrolysis and by on-site natural gas reforming.

Private partners

Ballard Power Systems

Ballard Power Systems, Inc. is a leader in the development, manufacture, sale and servicing of hydrogen fuel cells that are used in various markets, from materials handling to residential cogeneration, backup power and transportation.

Ballard next generation heavy duty HD6 bus module. Photo courtesy of Ballard Power Systems.

Ballard and its customers and partners have participated in a wide variety of demonstration programs and field trials to prove the practicality of PEM hydrogen fuel cell technology. Ballard's participation in programs such as HyFLEET: CUTE, ECTOS and STEP has resulted in over 2.5 million km of actual transit bus revenue service. Ballard has partnered in developing buses for demonstrations at the Santa Clara Valley Transportation Authority (VTA) and for the UNDP-GEF supported fuel cell bus project in Beijing. The company is also part of a consortium to deliver 20 fuel cell hybrid buses to BC Transit in British Columbia, as well as supplying fuel cells for five buses in Sao Paolo, Brazil and participating in two projects under the FTA's National Fuel Cell Bus Technology Development Program.

Daimler (formerly DaimlerChrysler)

Evobus, the Daimler Buses unit that comprises the brands Mercedes-Benz, Setra, and Orion, is a leading producer of buses and coaches with a gross vehicle weight of above eight tonnes. Products include city buses, intercity buses, touring coaches, minibuses, and chassis.

In 1997 Daimler demonstrated the application of fuel cell drive technology in city buses with the the prototype Nebus (New Electric Bus). Nebus features a 250 kW fuel cell, offers a range of 250 km (155 miles) and has a maximum speed of 80 km/h (50 mph).

Mercedes-Benz Citaro fuel cell buses. Photo courtesy of Daimler.

Daimler introduced the successor to Nebus, the Mercedes-Benz Citaro fuel cell urban bus, in 2002. Thirty of the fuel cell Citaro's were deployed in the European CUTE and ECTOS fuel cell bus projects in 2003, as well as three each for Perth, Australia's STEP fuel cell project and the China Fuel Cell Bus Project in Beijing. By May 2009, these 36 vehicles had attained more than two million km of road time.

The Citaro's fuel cell unit provides over 200 kW of power. The vehicle's electric motor, transmission, driveshaft and mechanical rear axle are mounted in the rear section of the bus and compressed gas cylinders containing hydrogen compressed at 350 bar are located on the roof. The buses have a range of 200 km (124 km), with a maximum speed of up to 80 km/h (50 mph).

Daimler and Evobus are developing a second generation fuel cell bus for the HyFLEET:CUTE project that will add rear wheel hub motors and a Li-ion battery. Vehicle weight will be reduced by several hundred kilograms (kg) to improve fuel consumption.

ISE Corporation

ISE is a leading integrator of fuel cells and fuel cell-based drive systems into heavy duty vehicles. The company also develops, supplies and services electric and hybrid-electric drive systems.

ISE developed its first prototype fuel cell bus for SunLine Transit Agency in Palm Desert, California, where it served in a six-month demonstration during 2002-2003. This was followed in 2003 by contracts to develop and integrate fuel cell hybrid drive systems into four Van Hool buses trialed by California's AC Transit and SunLine Transit, and to install a "fuel cell-ready" drive system into a New Flyer Invero bus for Hydrogenics.

The company has worked with Ford Power Products to develop a prototype HHICE bus using a hydrogen-burning engine produced by Ford. This bus was demonstrated by both SunLine Transit and Winnipeg Transit (Manitoba, Canada) during 2005.

ISE has also integrated a fuel cell hybrid-drive system into a bus deployed in 2007 by CTTRANSIT of Hartford, Connecticut.

For upcoming deployments, ISE is supplying the electric drive and battery technology for the 20-bus BC Transit fuel cell bus fleet, with bus manufacturer New Flyer performing the integration. ISE will also supply Transport for London with five fuel cell buses to be deployed in regular transit service in the city.

Shell Hydrogen

Shell's first hydrogen station debuted in Reykjavik to serve three fuel cell buses trialed under the ECTOS and HyFLEET:CUTE programs. The station produces hydrogen on-site via electrolysis, using renewably-generated electricity to power the electrolyzer. Although the bus trials have ended, the station continues to serve fuel cell vehicles deployed in Reykjavik. Shell stations were also opened in Amsterdam, using onsite hydrogen generation by electrolysis, and Luxembourg, using delivered hydrogen, to serve fuel cell buses deployed under the CUTE and HyFLEET:CUTE demonstrations. Both stations were closed following completion of the trials.

Shell hydrogen refueling station in Luxembourg. Photo courtesy of Shell.

A fourth hydrogen station, delivering both compressed and liquid hydrogen, opened in Tokyo in 2003 to serve vehicles deployed as part of the Japan Hydrogen and Fuel Cell Project (JHFC). It was the first liquid hydrogen station to be deployed in that country.

In 2004, Shell integrated hydrogen refueling into an existing Shell station in Washington, DC, where both liquid and compressed hydrogen are dispensed. This was followed by station openings in Shanghai, China in 2007, and hydrogen refueling integrated into an existing station in West Los Angeles, California in 2008, where compressed hydrogen is generated by electrolysis. The stations serve fuel cell and HICE vehicles deployed in those cities.

TOTAL Deutschland GmbH

TOTAL's first hydrogen filling station opened in Berlin, Germany in 2002, and was replaced in 2006 by a hydrogen station integrated into a newly-constructed public TOTAL service station in Berlin-Spandau. The station supplies hydrogen fuel to 14 MAN HICE buses operated in regular transit service by Berlin's transit authority, Berliner Verkehrsbetriebe (BVG). The buses are deployed under the HyFLEET:CUTE and the Clean Energy Partnership Berlin (CEP) projects. The station also serves Berlin's fleet of 17 fuel cell and HICE cars also operated under the CEP.

The station was designed for a maximum fueling capacity of 20 buses per day. Both liquid hydrogen (-253°C), and compressed hydrogen (350 or 700 bar) are dispensed. Gaseous hydrogen is produced on-site through steam reforming of LPG or Bio-DME at a production rate of up to 100 Nm^3/h, allowing a fueling capacity of seven hydrogen buses/day. In addition, liquefied hydrogen can be vaporized and compressed for gaseous fueling in case of high demand; this also serves as the station's back-up system. Re-liquefaction equipment is used to address liquid hydrogen boil-off. Any surplus compressed hydrogen is used by the station's two stationary fuel cells, which produce electricity sold to the grid and heat used in the service station's shop.

In 2007, TOTAL, in conjunction with BMW, opened Munich's first public hydrogen filling station featuring Germany's first underground storage tank for liquid hydrogen. In June 2008, the pair also introduced a liquid hydrogen filling station along the Ruisbroek-Brussels highway in Belgium.

Toyota Motor Corporation (JHFC Fuel Cell Bus Demonstration Project)

The Japan Hydrogen & Fuel Cell Demonstration Project (JHFC), organized by the Ministry of Economy, Trade and Industry, involves a wide range of activities related to the use of fuel cell vehicles, and includes demonstrations of fuel cell buses developed jointly by Toyota and Hino Motors. The project's Toyota-Hino FCHV-BUS utilizes a 180 kW Toyota fuel cell stack and NiMH battery and can attain a maximum speed of 80 km/h (50 mph).

Toyota fuel cell bus at Shell hydrogen station. Photo courtesy of Shell.

Three sites - Tokyo, Aichi EXPO and Centrair Airport – began demonstrating the Toyota-Hino fuel cell bus technology starting in 2003. The objective of the demonstrations was to collect data relating to safety and environmental issues for use in establishing safety standards for fuel cell buses. Raising public awareness was also a project objective.

During 2003-2004, one FCHV-BUS bus was deployed in regular service in Tokyo, operating for 17,438 km. Average fuel efficiency was 3.4 km/L diesel equivalent (8.0 mi/dge) and bus availability was 79%. Maintenance issues required 19% of the buses' available time, and promotional activities 2%. Liquid hydrogen was trucked in to the project's fueling station, dispensed as both liquid and high pressure gas.

The March-September 2005 Aichi Expo demonstration used eight of the Toyota-Hino fuel cell buses to shuttle passengers between the Nagakute and Seto areas on an 8.8-km (5.5 mi) roundtrip route. About one million visitors used the buses during the EXPO and a total of 124,500 km (77,360 miles) was traveled during the demonstration. A total of 11.43 tons of hydrogen were consumed, with average fuel economy of 3.17 km/L diesel fuel equivalent. (7.5 mi/dge) The buses were served by two hydrogen stations, Seto-North, which dispensed hydrogen derived from coke oven gas purification and transported to the site, and Seto-South, which received natural gas via pipeline and produced hydrogen on site via natural gas reformation. Hydrogen production capacity for each station was 8.9 kg/h.

The demonstration at Centrair Airport began in June 2006 using one FCHV-BUS on a single daily round trip route and another that made seven roundtrips per day during the week and five on weekends. The refueling facilities for this trial were reconstructed from the Seto-South Station.

UTC Power

UTC Power develops fuel cells for on-site power, transportation, space and defense applications.
In 1998 UTC Power integrated, in collaboration project with the U.S. Department of Transportation and Georgetown University, a 100 kW phosphoric acid fuel cell (PAFC) power plant into a full-size bus. The vehicle was used as a student shuttle at Georgetown University and was capable of running on a variety of fuels, including methanol and CNG.

UTC Power has incorporated its PureMotion® Model 120 PEM fuel cell in four buses in commercial transit service: three hybrid buses at AC Transit in Oakland, California, and one at SunLine Transit in Thousand Palms, California.

Vattenfall Europe

Vattenfall Europe, a leading power generating companies, has more than 15 years' experience in hydrogen energy engineering. The company is a partner in the CUTE, HyFLEET:CUTE and Clean Energy Partnership (CEP) Berlin hydrogen projects and the Hyways program to develop a European Hydrogen Energy Roadmap.

Vattenfall supplies clean fuel at Berlin's Messedam hydrogen fueling station by providing certified "green" electricity generated from a Swiss hydroelectric power station and an Irish offshore wind farm. The power is used to operate the station's hydrogen electrolyzer. Vattenfall also operates PEM fuel cells at Berlin's Heerstrasse hydrogen station that provide heat and power the station, using captured boil-off from the station's stored liquid hydrogen.

Vattenfall and Shell are planning construction of a new hydrogen station in Hamburg to supply the city's growing hydrogen bus fleet, operated by Hamburger Hochbahn.

Appendix 2. Interview Guides

The following sites were interviewed: Amsterdam, Netherlands; Berlin, Germany; Beijing, China; British Columbia, Canada; Hamburg, Germany; Hartford, Connecticut; London, UK; Luxembourg; Madrid, Spain; Oakland, California; Palm Springs, California; Perth, Western Australia; Reykjavik, Iceland; and Tokyo, Japan. For each site, we interviewed the transit operator and the primary technology providers, which included Daimler, Ballard Power Systems, UTC Power, ISE Corporation, Shell Hydrogen, TOTAL Deutschland GmbH and Vattenfall Europe. The questions were tailored slightly to the various demonstration partner categories: the fuel cell company, bus company, transit operator, integrator and infrastructure supplier.

Interview Guide for Hydrogen Bus Demonstration Survey Project

This questionnaire explores your views on your city's experience with the HyFLEET:CUTE project and what your experience indicates about the pathway to fuel cell bus commercialization.

1. Purpose:
   - What motivated your city/public transportation agency to participate in the demonstration?
   - What were your overall expectations and did the program meet them?

2. Outcome:
   - Were there positive surprises during the demonstration?
   - Unexpected challenges?

3. Demonstration Experience: What information or advice would you give other public transportation operators interested in deploying fuel cell buses based on your demonstration experience regarding:
   a. Vehicle performance and integration into regular operations – specifically, reliability, range, fuel efficiency, drivability, durability, or other issues
   b. Vehicle maintenance
   c. Vehicle facilities/workshops
   d. Hydrogen infrastructure and fueling issues
   e. Safety issues?

4. Workforce: Based on your experience, what advice would give other operators or agencies about training issues surrounding fuel cell buses for:
   - Drivers
   - Mechanics
   - Emergency & safety staff
   - Cleaning or other staff?

   How your drivers respond to the buses? Mechanics?

5. Response to the buses:
   - How did riders respond to the buses? Did you do a rider survey -- are the results available?
   - How did the general public respond to the buses? Was the bus a valuable educational tool?

6. Critical areas for improvement: Please tell us the three issues you believe are most important to address for fuel cell buses to succeed in mainstream transit operations. Why are they important and how do you believe they should be resolved?

7. Future of hydrogen ICE buses:
   - What do you see as the role of hydrogen ICE buses in fuel cell bus development?
   - What is your opinion about the commercial viability of hydrogen ICE buses?

8. If you have specific plans to deploy more hydrogen buses:
   - What improvements do you expect compared to the recent demonstrations?
   - What challenges are you facing?
   - How do you plan to evaluate the results of this new deployment?

9. Future of fuel cell buses:
   - For your agency, what are the most important factors in deciding to purchase more fuel cell buses in the future? What about hydrogen ICE buses?
   - What factors are holding your agency back from moving ahead more quickly or devoting more resources to this technology?
   - In your opinion, will the commercial success of fuel cell or hydrogen ICE buses depend upon any particular external circumstances (i.e., increased fuel prices, greenhouse gas regulations…)? Why?

10. Hydrogen infrastructure and fueling for larger deployments:
    - In your view, what key infrastructure issues must be addressed to support the next phase of deployments of 10 - 20 fuel cell or hydrogen ICE buses?
    - What are the key infrastructure issues for large-scale use of hydrogen buses?

11. Industry and government support for fuel cell buses:
    - In your opinion, what government policies would best help support fuel cell bus development and commercialization (such as long-range government strategic plan, long-term funding commitment, carbon reduction mandates, etc)?
    - Are there collaborative industry activities that would speed development and commercialization (for example, pooled procurements, standardization across platforms, etc)?

12. Are there any other questions that we should have asked that we have not?

Appendix 3. Summary of Hydrogen Production and Storage

City/Operator	Production / Delivery	Hydrogen Source	Storage Size	Fueled By	Filling Time	Notes
Amsterdam	On-site	Electrolysis	250 kg	Driver (not cleaners as with diesel)	12 min.	Temporary station only; unsheltered;
AC Transit	On-site	Steam reformation off of natural gas utility line.	366 kg	Chevron technicians; AC Transit staff now trained	14 min.	Chevron operates & maintains station. Can fuel 2 buses simultaneously. Also used for light-duty vehicles.
Barcelona	On-site	Electrolysis	150 kg	BP subcontractors	12 min.	
BC Transit Whistler station	Liquid hydrogen trucked in from Quebec.	Hydropower	250 kg	TBD	N/A	This station is scheduled to open in 2009/2010.
Beijing	Trucked in	Natural gas reformation	165 kg/day			
	On-site planned	Electrolysis, natural gas reformation				
Berlin	On-site mobile fueling station	LPG reformer produces hydrogen for 7 buses; also equipped with electrolyser			12-15 min.	Public station; fuels 15 HICE buses and 20 cars.
CTTRANSIT	Liquid hydrogen trucked in to UTC facility.	By-product of clor-alkali process through electrolyzers powered by hydro	[Unknown; UTC station]	UTC technicians only	22 min. (36 min. avg.)	UTC Power hydrogen facility. Fueling time includes clearing station of other vehicles.
Hamburg	On-site	Electrolysis	400 kg	Drivers	10 min.	
London	Trucked in liquid hydrogen	Steam reformation at an industrial plant	3200 kg	Service personnel	30 min.	Station was decommissioned after demonstration, as had been planned.
Luxembourg	Trucked in gaseous hydrogen	Produced at nearby chemical plant	500 kg	Site technicians	25 min.	
Madrid	On-site and trucked in	Steam reformation	360 kg	Site technicians	20 min.	
Perth	Trucked in	Produced from nearby crude oil/natural gas refinery		Drivers	15 min.	
Porto	Trucked in gaseous hydrogen	Produced via electrolysis	174 kg	Service personnel	15 min.	
Reykjavik	On-site	electrolysis		Drivers	8 min.	
Santa Clara VTA	Trucked in	Compressed on-site	9,000 kg		12-20	Built to fuel 6 buses;

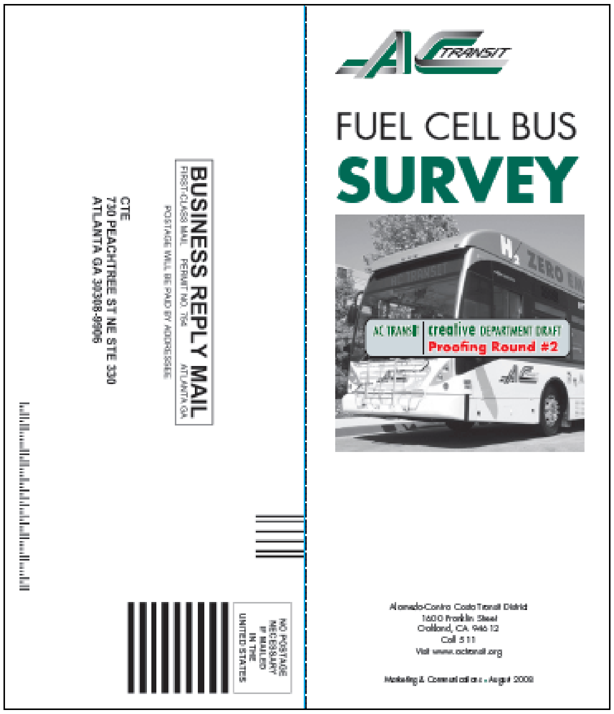
		liquid hydrogen				min.	only half of this was needed, so venting was required.
Stockholm		On-site	Electrolysis	95 kg	Drivers	20 min.	
Stuttgart		On-site	Steam reformation	281 kg	Drivers	15 min.	
SunLine Transit		On-site	Steam reformation of natural gas.	180 kg	Drivers		This is also a public station.
Toyota Projects	Ariake Station	Trucked in liquid hydrogen					
	Seto-South & Centrair Airport	On-site	Piped in hydrogen by-product and on-site steam reformation				The Seto-South Station was transferred to Centrair Airport to serve the airport's project.
	Seto-North	Trucked in compressed hydrogen	Coke oven gas (COG)				

Appendix 4. Overview of Fuel Cell Bus Facility Features Implemented

Program/Project	Fuel Cell Bus Facility Features
CUTE sites	Although each city chose a slightly different strategy, the key measures implemented in the 9 cities were: • Some accommodation made for bus height through doorways etc. • Walkways, either fixed or on wheels, with guard-rails, for work on the top of the buses. • Crane for hoisting components from and to the bus roof • If buses were parked outside or in a non-heated building, they needed to be heated externally to avoid damage to the fuel cells on cold nights. At some sites with regular outside parking, buses stayed in the workshop when very cold nights Safety-related measures: • Fans in the roof or hatches for increased natural ventilation, supported by lower level openings that allow fresh air entry • Spark proof tools, at least for work on the bus top • Anti-static clothing for mechanics • Hydrogen sensors along ceilings which activate safety alarms • If safety alarms were activated, electrical installations which were not explosion-proof were switched off and, if not already, explosion-proof lighting turned on • Hydrogen release pipes were attached to the buses' piping system to vent the hydrogen in case a bus storage tank's pressure relief valve failed and the hydrogen vented
ECTOS (Reykjavik)	• Walkways to provide safe access at roof level • Overhead gantry hoist to lift heavy roof modules and place them on the walkways or floor • Standard bus wheel lifts to adjust bus height relative to maintenance superstructure walkways • Regulated pure nitrogen or clean air supply for leak tests with associated hoses and fittings • Regulated pure nitrogen for tank purging with associated hoses and fittings • Hydrogen venting capability with associated hoses and fittings
AC Transit	• Bay is separated by firewall from rest of bus facility • Hydrogen detection • 3-fan ventilation system • Ignition-free space heating • Anti-static floor covering • High-speed roll-up doors; magnetic door release

	• Strobe alarms • Vehicles must be depressurized before entering
CTTRANSIT	• Existing ventilation ductwork directed to the bus • Air was sucked off the roof via a small ceiling fan • Hydrogen sensors • Plastic covers on fluorescent lights • Backup power so ventilation is always on • Turn off hydrogen and fuel cell before entering garage
Santa Clara VTA	New building with: • Explosion-proof electrical fixtures • Hydrogen and flame sensors • Anti-static coating on doors • New bus wash to allow for added height of fuel cell bus • Roof design that allows for hydrogen ventilation
SunLine Transit	Existing hydrogen maintenance facility consisting of an outdoor tent that that allows venting of any leaked hydrogen through its roof.

Appendix 5: Sample Rider Survey



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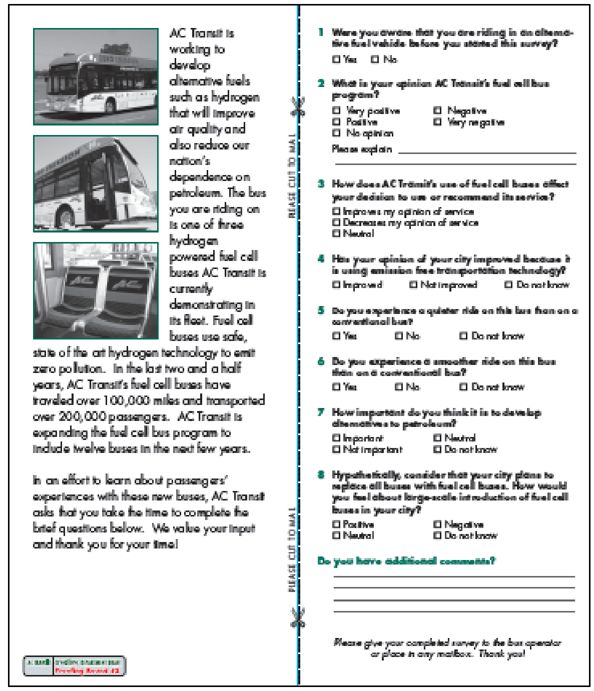

AC Transit is working to develop alternative fuels such as hydrogen that will improve air quality and also reduce our nation's dependence on petroleum. The bus you are riding on is one of three hydrogen powered fuel cell buses AC Transit is currently demonstrating in its fleet. Fuel cell buses use safe, state of the art hydrogen technology to emit zero pollution. In the last two and a half years, AC Transit's fuel cell buses have traveled over 100,000 miles and transported over 200,000 passengers. AC Transit is expanding the fuel cell bus program to include twelve buses in the next few years.

In an effort to learn about passengers' experiences with these new buses, AC Transit asks that you take the time to complete the brief questions below. We value your input and thank you for your time!

PLEASE CUT TO MAIL

1 Were you aware that you are riding in an alternative fuel vehicle before you started this survey?
☐ Yes ☐ No

2 What is your opinion AC Transit's fuel cell bus program?
☐ Very positive ☐ Negative
☐ Positive ☐ Very negative
☐ No opinion
Please explain ______

3 How does AC Transit's use of fuel cell buses affect your decision to use or recommend its service?
☐ Improves my opinion of service
☐ Decreases my opinion of service
☐ Neutral

4 Has your opinion of your city improved because it is using emission free transportation technology?
☐ Improved ☐ Not improved ☐ Do not know

5 Do you experience a quieter ride on this bus than on a conventional bus?
☐ Yes ☐ No ☐ Do not know

6 Do you experience a smoother ride on this bus than on a conventional bus?
☐ Yes ☐ No ☐ Do not know

7 How important do you think it is to develop alternatives to petroleum?
☐ Important ☐ Neutral
☐ Not important ☐ Do not know

8 Hypothetically, consider that your city plans to replace all buses with fuel cell buses. How would you feel about large-scale introduction of fuel cell buses in your city?
☐ Positive ☐ Negative
☐ Neutral ☐ Do not know

Do you have additional comments?

______

Please give your completed survey to the bus operator or place in any mailbox. Thank you!

Federal Transit Administration

Office of Research, Demonstration and Innovation
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

www.fta.dot.gov/research

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