



Alternative Propulsion Systems

Boston's Next Generation Bus Fleet

MARCH 2014

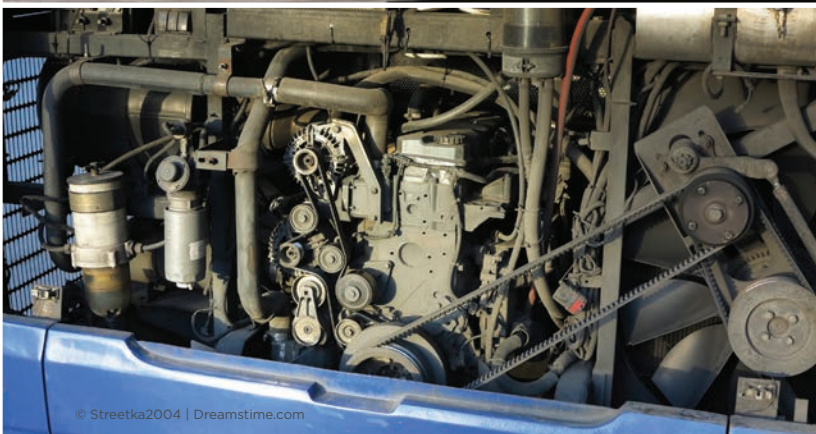


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INTRODUCTION

The MBTA is faced with the challenges of replacing an aging fleet while working within a constrained financial environment and complying with environmental regulations. The MBTA has shown a strong interest in reducing pollutants and greenhouse gas emissions emitted by their vehicles and has invested in buses with emission controlled diesel technology (ECD), compressed natural gas (CNG) and diesel-hybrid buses. The challenge is determining whether to continue to invest in the matured/maturing propulsion technology it has already adopted or if it should look to new technologies to replace its current fleet, without compromising its financial future.

There are many technologies that other transit agencies have adopted or explored. Biodiesel, liquefied natural gas, battery-electric, and hydrogen fuel-cell technology, to name a few. All of these technologies require additional, and in some cases significant, capital investment including new buses and new facilities to support the alternative fuels. While biodiesel and liquefied natural gas show promise in reducing emissions, their adoption into the MBTA fleet would most likely not yield significantly higher benefits over the current propulsion systems. Thus, the propulsion technologies reviewed in this paper are the current propulsion systems used by the MBTA, diesel, diesel-hybrid, and CNG, and battery-electric and hydrogen fuel-cell systems.

The intent of this paper is to provide an overview of the current state of the MBTA fleet, present summaries of the propulsion systems, provide an analysis of the lifecycle costs and potential greenhouse gas reductions, and provide recommended next steps that the MBTA can take to incorporate these new propulsion systems into their fleet.

CURRENT STATE OF THE MBTA FLEET

The MBTA has approximately 1,065 buses in service. Approximately 90 percent of its fleet is 40 foot buses and the remainder is 60 foot articulated buses. The MBTA purchased buses from four manufacturers (Nova/RTS, New Flyer, Neoplan, NABI) and utilize five different propulsion systems (diesel, CNG, diesel/electric hybrid, diesel/trackless trolley, electric trolley). Exhibit 1 presents a table of the current bus fleet and its characteristics.

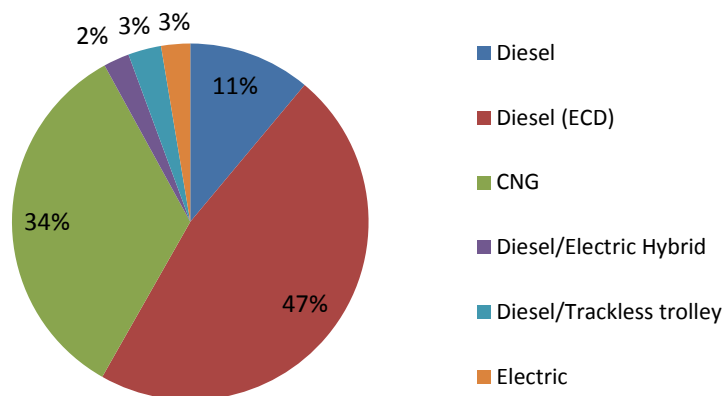
EXHIBIT 1 BUS FLEET OVERVIEW

Manufacturer	Length	Quantity	Year Purchased	Propulsion	Status
Nova/RTS	40'	118	1994-5	Diesel	Schedule for retirement by 2014
New Flyer	40'	17	2001	CNG	First Silver Line buses
Neoplan ECD	40'	192	2004-5	Diesel (ECD)	Emission controlled diesel
NABI	40'	299	2003-4	CNG	
New Flyer ECD	40'	310	2006-8	Diesel (ECD)	Emission controlled diesel
Neoplan ECD	60'	44	2003	CNG	
New Flyer Hybrid	60'	25	2010	Diesel/Electric Hybrid	
Neoplan DMA	60'	32	2004-5	Diesel/Trackless trolley	Dedicated to Silver Line
Neoplan Trackless Trolley	40'	28	2004	Electric	Dedicated routes
1065					

Source: MBTA

All pre-2004 diesel bus engines have been retrofitted with diesel particulate filters (DPF). As shown, approximately 11 percent of the MBTA fleet uses diesel propulsion without emissions control while the remaining fleet either uses diesel propulsion with emissions control, CNG, hybrid, dual-mode or electric propulsion. The diesel fleet without ECD is schedule to be retired by the end of this year (2014). Exhibit 2 presents the percentage of the buses using the respective propulsion systems.

EXHIBIT 2 FLEET DEMOGRAPHICS



Source: MBTA

According to the MBTA, the useful life of a diesel or CNG bus is estimated to be 12 years, assuming that each bus undergoes a full mid-life overhaul. Electric buses are anticipated to have a useful life of 15 years, also assuming a full mid-life overhaul.



MBTA 40' ECD Bus

Photo: MBTA

The MBTA keeps approximately 20 percent of its peak service requirement reserve. This is based on previous experience with reserve demand due to routine and non-routine maintenance, overhauls, and heavy repair.

A critical component of the current state of the MBTA is to understand its supporting storage and service infrastructure. The MBTA currently has eight bus maintenance facilities, one carhouse, and a main repair facility to store and service its buses. Each garage can support particular lengths and propulsion systems. After the introduction of alternative propulsion systems to the fleet (non-diesel), enhancements to garages that support these systems was necessary and required to maintain regulatory compliance. Exhibit 3 presents the MBTA’s existing bus maintenance facilities and the quantity and bus models it services.

EXHIBIT 3 BUS MAINTENANCE FACILITIES

Garage	Storage, Service Repair (# Buses)	Service Routes	Propulsion Serviced
Albany St. Garage	(114) – 2004/2005 Neoplan ECD Diesel	21	Diesel
Arborway Garage	(130) – 2003 NABI CNG	32	CNG
Cabot Garage	(148) – 2003/2004 NABI CNG (40) – 2006 New Flyer ECD Diesel	36	CNG Diesel
Charlestown Garage	(86) – 1994/1995 Nova RTS Diesel (139) – 2006 New Flyer ECD Diesel	59	Diesel
Fellsway Garage	(75) – 2004/2005 Neoplan ECD Diesel	16	Diesel
Lynn Garage	(22) – 1994/1995 Nova RTS Diesel (69) – 2004/2005 Neoplan ECD Diesel	26	Diesel
Quincy Garage	(17) – 1994/1995 Nova RTS Diesel (62) – 2004/2005 Neoplan ECD Diesel	25	Diesel
Southampton St. Garage	(16) – 2001 New Flyer CNG –RTE/SL1 (17) – 2003 Neoplan 60’ CNG Artic. – SL1 (27) – 2003 Neoplan 60’ CNG Articulated (32) – 2004/2005 Neoplan 60’ DMA –SL2 (25) – 2009 New Flyer Hybrid SL-4	8	CNG DMA Diesel Hybrid
North Cambridge Carhouse	(28) – 2004 Neoplan Electric Trolley Bus [ETB]	4	Electric
Everett Main Repair Facility	(55) – 1994/1995 Nova RTS Diesel	0	CNG Diesel

Source: MBTA Bus Fleet Management Plan FY2010-FY2020



MBTA 40' CNG Bus

Photo: MBTA

The Southampton St. Garage services three propulsion systems (CNG, Dual-Mode, and Diesel Hybrid) and is the only facility that currently supports maintenance of a 60’ articulated bus. The Cabot garage supports both CNG and Diesel propulsion systems and the Everett and Arborway Garages are the only other facility to support CNG propelled buses. Bus maintenance capacity and condition are key factors in determining whether a fleet of buses with a new type of propulsion system can be supported. As shown, maintenance facilities support specific propulsion types and routes. As a result, specific propulsion types can only be run on specific routes in order to minimize deadheading (i.e., travel without a fare) to and from maintenance facilities.

Discussions with the MBTA have revealed that upgrades to and expansion of existing facilities and possible increases to the number of facilities are necessary to support its current fleet let alone bring in new types of propulsion systems. Even if the MBTA were

to add additional buses using propulsion systems it currently supports, there might not be enough capacity at its garages to maintain and service them. A comprehensive Bus Maintenance Facility Strategic Plan is necessary to comprehend the full set of maintenance facility current needs and their ability to support current and different propulsion systems.

FUTURE FLEET NEEDS

According to the 2010 MBTA Bus Fleet Management Plan, the MBTA plans programmatic replacement on an annual basis for the buses, approximately 80-100 buses per year to maintain its current fleet size. The purpose would be to smooth out the number of buses reaching the end of their useful life. Most if not all of these buses will utilize clean technology.



MBTA DUAL-MODE ARTICULATED BUS

Photo: MBTA

REPLACEMENT OF SILVER LINE DUAL-MODE ARTICULATED (DMA) BUSES

The Silver Line currently runs unique dual-mode articulated buses to support Silver Line-Phase II which includes a one-mile long dedicated bus way tunnel to support the South Boston Waterfront and Logan Airport. While operating underground on its bus way, these buses raise pantographs, similar to those of an electric trolley bus, to pull electricity from the electric grid and propel its electric motor. While operating on the surface, the driver lowers the catenaries and the bus operates using a diesel engine.

These DMA's are approaching ten years of age and are slightly past their mid-life. Given that the bus procurement process can take between 5-7 years, the time to procure new buses needs to start soon. Unfortunately, Neoplan, the manufacturer that manufactured these buses for the MBTA is no longer in business. Furthermore, extension of Silver Line service into Chelsea is currently in the planning phase and may be in operation within the next few years and would require expansion of the Silver Line fleet. As such, an alternative solution or bus manufacturer needs to be found.

PROPULSION SYSTEMS

Much research has been conducted over the past few years, exploring the use of alternative fuels and propulsion systems in transit vehicles and their potential for reducing pollutants and greenhouse gas emissions. The following section summarizes the present state of propulsion systems, summarizing the research conducted on each. Given its prevalence in the transit industry and the MBTA bus fleet, diesel propulsion is explored first and used as a benchmark against which other technologies are compared.

DIESEL

Diesel propulsion systems power the majority of transit vehicles in the U.S. Its widespread use is supported by a robust fuel distribution infrastructure. Within the past decade, federal regulations and new technologies have decreased the impact of diesel fuel emissions and the maturity of the technology is evident in the reliability of the propulsion system and the trust transit agencies have in their diesel powered buses.

Diesel engines have been used for propulsion since the early part of the 20th century. Diesel engines are known for their fuel economy, power, torque and reliability. Given the maturity of the technology, improvements to the diesel propulsion engines focus on increased efficiency and decreased emissions. During the 1980's and 1990's several factors led to increased fuel consumption: features such as air conditioning, wheel chair lifts increased the weight of vehicle and higher engine ratings (greater horse-power). While there are many bus manufacturers supplying the U.S. transit bus fleet there are two major engine manufacturers that supply diesel engines to bus makers: Cummins and Detroit Diesel Company.

Emission standards of 2007 and 2010 have led to several technological changes in diesel transit vehicles. These include:

- Diesel Particulate Filters (DPF) – Physically filter engine exhaust of particulate matter
- Exhaust Gas Recirculation (EGR) – Recirculates engine's exhaust gas into engine's intake system reducing NOx emissions.
- Selective Catalytic Reduction (SCR) – Uses mixture of urea and water (also known as Diesel Exhaust Fluid (DEF)) to remove NOx from emissions

PERFORMANCE AND RELIABILITY

Regardless of engine type or propulsion system, engine performance and fuel economy is dependent on several factors including bus characteristics (curb weight, use of air conditioning, engine horsepower rating, after engine treatments for emissions) and route characteristics (duty cycle (number of stops, frequency of stops, average speeds, topography, passenger loads). Fuel economy for full-size transit vehicles is typically approximately 4 miles per gallon. The Cummins and Detroit Diesel Company engines employ several emissions reduction systems and as a result fuel economy is slightly lower than engines without these systems due to the added weight and other demands on the engine. However, the two manufacturers managed to offset these losses and increased fuel economy by 2 to 5 percent for the MY2010 buses.

A key attribute of the diesel propulsion system is its reliability. Its long history and mature technology has made it one of the most dependable and popular propulsion systems available to transit agencies.

SUMMARY

- Mature technology
- Reliable
- Good range and fuel efficiency
- Meets current EPA emissions standards; however, still releases more particulate matter and nitrogen oxide pollutants than other systems
- MBTA has current infrastructure to support system
- Generally non-domestic fuel source
- Increasing fuel cost
- Comparably louder than some other propulsion systems



CUMMINS WESTPORT ISL G NATURAL GAS ENGINE

Photo: CUMMINS WESTPORT

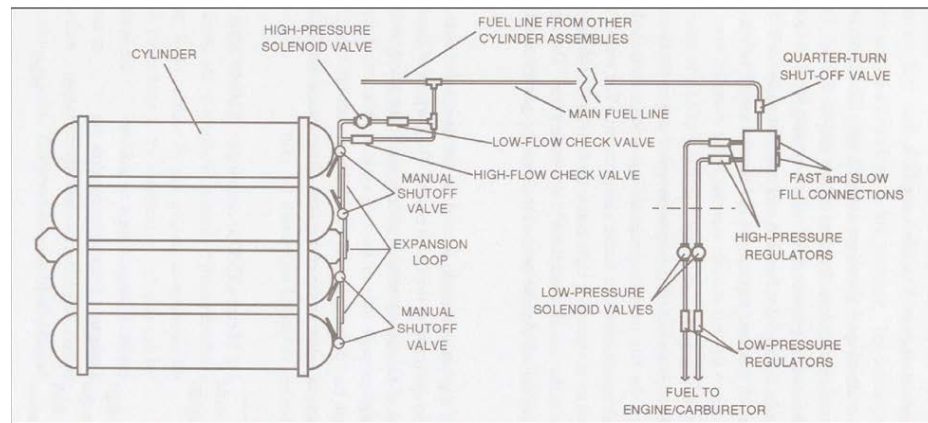
NATURAL GAS

Natural gas is a widely available fuel that comes primarily from domestic fossil fuel reserves. Natural gas is the second most utilized propulsion system by transit agencies with a steady increase in the number of operating buses over the last two decades. Approximately 19 percent of the national transit bus fleet uses some form of natural gas fuel. Compressed natural gas (CNG) and liquefied natural gas (LNG) are the two most common forms of natural gas propulsion system.

LNG has higher energy content per unit volume over CNG, however both have lower energy content per volume than diesel fuel, 60 percent vs. 25 percent, respectively. Less than 10 percent of all buses that have natural gas propulsion systems use LNG, all of which are located in the southwest US (California, Arizona, and New Mexico). CNG is more common than LNG and has a longer history of use in vehicles. Given the MBTA's substantial investment in their CNG fleet the remainder of this section is focused on CNG technology.

A CNG fuel system is illustrated below and is comprised of high pressure cylinders, a series of valves and regulators, and fuel lines. The Cummins Westport ISL G is the most common natural gas engine installed in transit fleet buses, as it meets the 2010 EPA emission standards. The engine uses a three-way catalyst to reduce nitrogen-oxide, hydrocarbon and carbon monoxide emissions.

EXHIBIT 4 CNG FUEL SYSTEM



Source: TCRP 146

PERFORMANCE AND RELIABILITY

Performance and operation of a CNG transit bus is very similar to that of its diesel counterparts; however, some drivers note a decrease in acceleration and power when driving uphill. CNG buses are typically heavier than similar diesel buses due to the weight of its fuel cylinders and have a lower torque, both which contribute to the lower acceleration. As a result, transit agencies that service areas with steep grades, such as San Francisco, have opted for other propulsion system technologies.

The heavier weight of CNG buses also contribute to lower fuel efficiency. Fuel economy is typically given in diesel gallon equivalents (DGE) for vehicles that use alternative fuels and propulsion systems. A typical CNG bus averages 2.5 miles per DGE compared to 3.6 miles per gallon on a typical diesel bus.

As described in TCRP Report 146, additional maintenance tasks are required of CNG buses including:

- Potentially greater inspection and replacement of brakes and suspension due to the heavier weight of CNG buses
- Inspection of onboard CNG fuel cylinders
- Recommended emptying of fuel cylinders prior to maintenance and repair activities
- Maintenance of refueling equipment

Vehicle reliability for transit fleets is typically measured by the metric miles between road calls (MBRC). Recent reports regarding reliability have not produced conclusive results regarding which propulsion system is more reliable (diesel vs. CNG); however, according to agencies using the technology, including the MBTA, CNG buses are an acceptable fleet solution.

SUMMARY

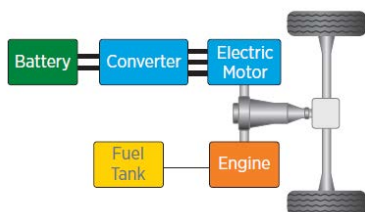
- Mature technology
- Relatively low fuel cost
- MBTA has current infrastructure to support system; however, may require additional to support larger CNG fleet
- Low emissions and no particulate matter
- Domestically produced fuel
- As reliable as diesel propulsion
- Slightly higher per bus cost than diesel

HYBRID-ELECTRIC TECHNOLOGY

Hybrid technology by definition relies on two or more sources of drive power and is combined with a rechargeable energy storage system. In hybrid electric transit buses the two sources of power are typically electricity and an internal combustion engine. The combustion engine is specific to a certain fuel type and most commonly diesel; however, CNG and other combustion fuels have been coupled in transit vehicles. Hybrids also leverage technologies such as regenerative braking, which captures and stores energy generated during the braking process. Hybrid buses typically are configured in parallel or series drivetrains. The following sections presents definitions of these.

PARALLEL HYBRID

Parallel systems have both the electrical motor and the internal combustion engine connected to the transmission and each can transfer mechanical power to the wheels to



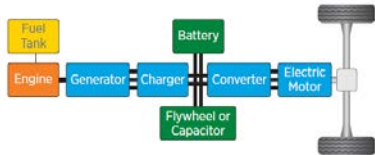
PARALLEL HYBRID SYSTEM

Image: US DOE Clean Cities

move the vehicle forward. A parallel hybrid system is designed to power the bus using the electric motor at low speeds (e.g., stop and go traffic) and using the internal combustion engine when a higher level of performance is required (e.g., at highway speeds or driving up a hill). In some cases, the electric motor only provides supplemental power or is used for acceleration boosts. The MBTA's fleet currently has 25 parallel hybrid buses from New Flyer Industries.

SERIES HYBRID

In a series hybrid system, the electric motor exclusively propels the bus. The internal combustion engine drives a generator which either charges the batteries or drives the electric motor. Since the internal combustion engine is not connected to the wheels, it can operate at a consistent and optimum (efficient) rate.



SERIES HYBRID SYSTEM

Image: US DOE Clean Cities

PERFORMANCE AND RELIABILITY

Performance and reliability are dependent on bus characteristics and route characteristics. This is certainly the case for hybrid-electric propelled buses. Fuel economy for hybrid-electric buses varies from city to city and state to state; however, all data points to the fuel economy of hybrid-electric as 10-50 percent more fuel efficient than its conventional diesel counterparts, depending on several factors such as whether the hybrid is series or parallel. Generally, series hybrids are more fuel efficient in stop and go conditions while parallel hybrids are under higher speeds and fewer stops (e.g., exclusive right-of-way or express buses using the highway).

There have been mixed results related to the reporting of reliability for hybrid-electric vehicles. New York City Transit reported that its reliability improved slightly comparing the MBRC for its Hybrids versus its diesel bus propulsion systems. While King County, WMATA and Long Beach Transit all claimed a significant decrease in reliability of its respective hybrid fleet, this data is several years old and hybrid technology has been refined and updated since. Anecdotally, MBTA operations staff has said that its hybrid fleet is generally less reliable than its diesel or CNG fleet; however, no data is currently available. The MBTA hybrid fleet is currently only serviced out of the Southampton Street Garage. Reliability of hybrid buses should be monitored closely over upcoming years to see if reliability improves.

SUMMARY

- Lower tailpipe emissions than standard diesel bus
- Good range and better fuel efficiency than standard diesel
- Can be used in combination with any type of combustion engine (i.e., can replace diesel combustion engine in hybrid with CNG driven engine)
- MBTA has current infrastructure and experience to support system
- Reports of less reliability than diesel and CNG
- Increasing fuel cost; generally non-domestic fuel source
- Higher vehicle costs
- Technology is maturing

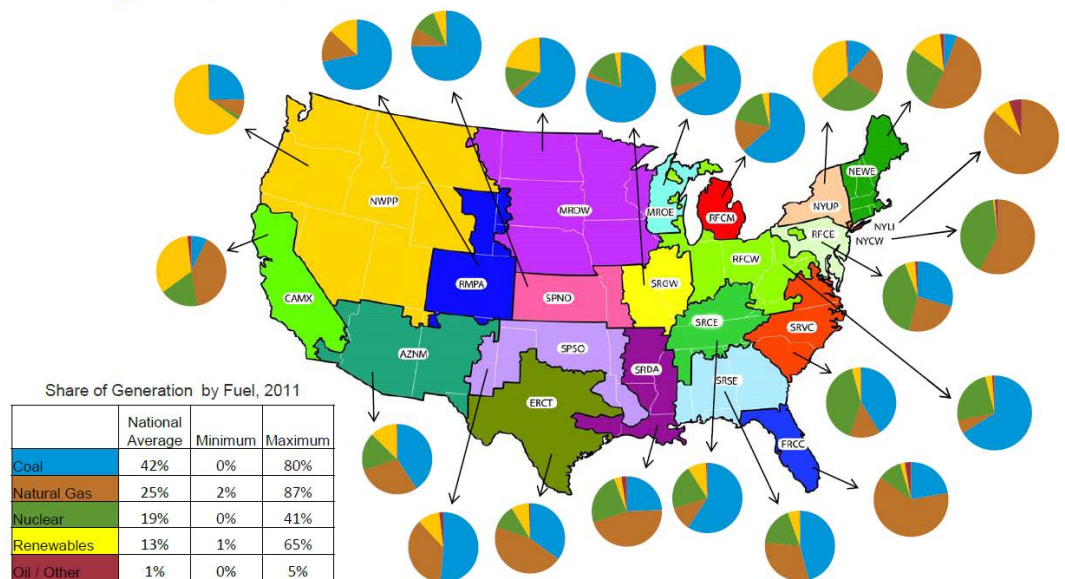
BATTERY ELECTRIC

Battery electric propulsion systems are a relatively new and promising technology introduced to the transit industry. Currently its relatively unproven as a standalone solution with the biggest concern being its energy capacity to power a large transit bus the entire day.

Up until recent years, electric powered buses have been limited to smaller capacities (22 to 30 foot size range) with maximum speeds of 25 to 40 miles per hour. Past limitations include the size (volume) and weight of the on-board battery. Technological innovations including composite material chassis have been created to reduce overall weight of electric buses by 10,000 lbs.

Battery electric propulsion draws most of its power from the electrical grid, thus, the environmental impact of the technology is based upon the fuel the grid uses to generate its electricity. Exhibit 5 presents the fuel mix for regional electricity generation across the United States.

EXHIBIT 5 REGIONAL ELECTRICITY GENERATION FUEL MIX



Source: EIA, Annual Energy Outlook 2013, based on Form EIA-923

As a result, environmental impact in the Northeast, where the majority of its electricity is generated from natural gas and nuclear power, can be significantly lower than in the Midwest where electricity is generated mostly from coal reserves.

BATTERY TECHNOLOGY

Battery technology significantly improves annually and could be the most critical component of the battery electric propulsion system. The batteries carry a significant

proportion of the buses weight and vary in terms of performance. Battery performance can vary based on several factors including:

- Specific energy – the ratio of a battery’s energy output to its weight typically measured in watt-hours per kilogram (Wh/kg)
- Specific power – the ratio of a battery’s power to its mass expressed in watts per kilogram (W/kg)
- Cycle life – the number of complete discharge-recharge cycles a battery can go through before its capacity declines to 80 percent of its original capacity
- Calendar life- the amount of time that a battery can provide power and capacity for its uses

Battery technology reflects the chemical composition of the battery. Exhibit 6 presents the latest battery technology characteristics for battery electric buses.

EXHIBIT 6 BATTERY ELECTRIC BUS BATTERY CHARACTERISTICS

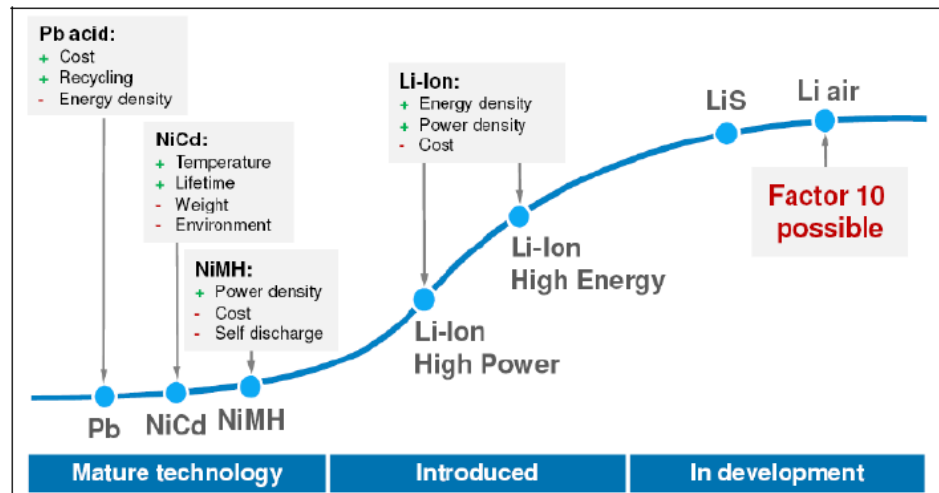
Chemical Composition	Specific Energy [Wh/kg]	Specific Power [W/kg]	Cycle Life [# cycles]	Relative Cost
Lead Acid	35	200	500-800	\$
Nicel-Cadmium	30	260	1000	\$\$\$
Nickel Metal Hydride	45-75	850	900	N/A
Sodium Nickel Chloride	995	170	1000	\$\$\$
Lithium –ion	100-180	700-1300	1000-4000	\$\$\$\$
USABC Minimum Goals	150	300	1000	\$
USABC Long-Term Goals	200	400	1000	\$

Source: TCRP Report 146

USABC is the United States Advanced Battery consortium

The most promising chemical composition for batteries includes silicon, sulfur and oxygen. Exhibit 7 presents a battery technology roadmap outlining the future potential of batteries.

EXHIBIT 7 BATTERY TECHNOLOGY ROADMAP



Source: Zivanovic and Nikolic

There are some significant hurdles that must be met to allay the concerns around battery electric buses:

- Battery storage capacity
- Battery duty cycles
- Battery disposal
- Effect of cold temperature on battery capacity and battery life
- Durability
- Life expectancy
- Energy and power density
- Recharge time
- Cost

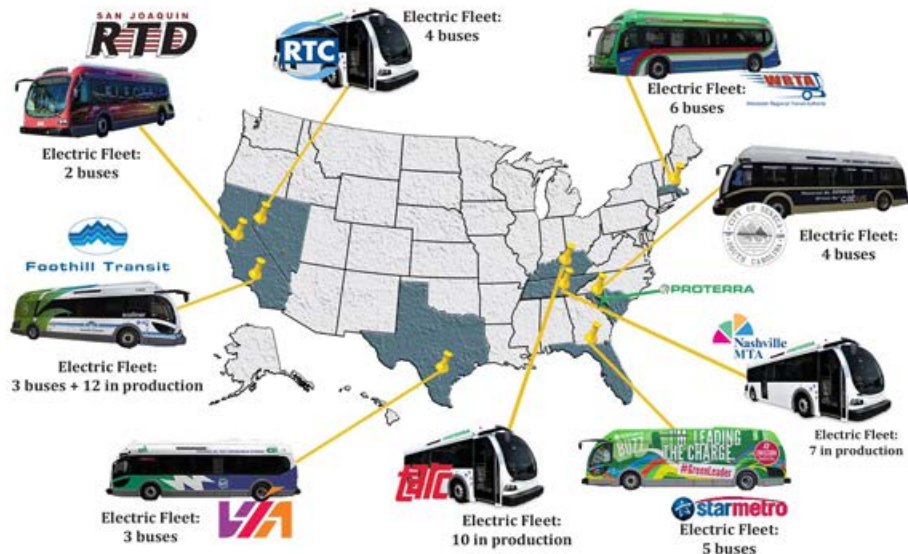


PROTERRA EcoRide BE35

Source: Proterra

While there are several manufacturers of battery electric buses around the world, only one is located in the United States that manufactures full-sized battery electric buses, Proterra. Proterra’s EcoRide BE35 is a zero emission, fast-charge battery electric bus, put into service in 2010. Nine agencies currently run or have ordered BE35’s for a total of 56 buses in the US. Proterra uses a lightweight composite body resulting in a 25% reduction in weight. Its regenerative braking system recaptures approximately 90 percent of the vehicle’s kinetic energy. Proterra claims a three hour, 30-40 mile range for its BE35 and requires a 10 minute charge to fully recharge from empty.

EXHIBIT 8 PROTERRA FLEET

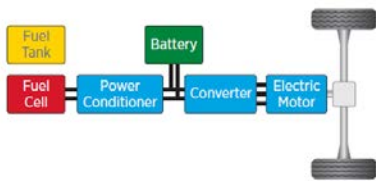


Source: Proterra

SUMMARY

- Zero emissions at point of use
- Higher on-board customer satisfaction due to smoother and quieter ride
- Low range

- High capital cost of buses and supporting infrastructure
- Not significant presence in domestic fleets
- Weight of battery packs decreases efficiency
- Durability and long-term performance is unknown
- Fuel (electricity) prices generally stable
- Not dependent on fossil fuel /electricity can be generated from renewable sources



FUEL CELL HYBRID

Photo: US DOE Clean Cities

HYDROGEN FUEL CELL

Hydrogen fuel cell technology has garnered a lot of attention recently as a clean and efficient solution to the transportation sector’s fossil fuel dependency. Hydrogen fuel cell technology converts hydrogen gas and oxygen (from air) through chemical reaction into electrical energy which is then transferred to an electric motor which in turn mechanically drives the bus’s wheels forward.

Hydrogen fuel cells produce zero tailpipe emissions and are very appealing for transportation applications because:

- Hydrogen can be produced from renewable and domestic resources
- Fuel cell technology is more efficient than conventional internal combustion engines in converting fuel to power.

Hydrogen fuel cell technology on buses utilize basic components as shown in Exhibit 9. The system is made up of the following components:

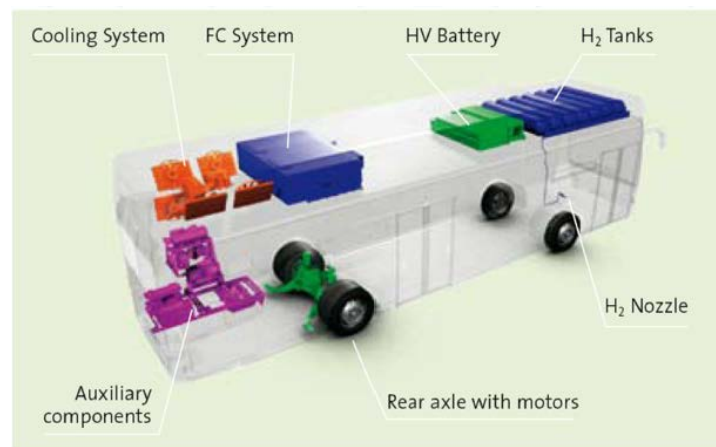
- Hydrogen storage tanks
- Fuel cell system
- Cooling system
- Electric storage system
- Auxillary systems
- Electric motors.



BALLARD FUEL CELL

Photo: Ballard

EXHIBIT 9 FUEL CELL HYBRID BUS



Source: Zivanovic and Nikolic

Hydrogen Fuel cell propulsion systems are attractive for transit applications for several reasons:

- Greater efficiency
- Quieter and smoother operations
- Regenerative braking results in extended brake life,
- Zero emissions in operations

Some of the biggest challenges are

- on-bus hydrogen storage (requires very high pressure)
- infrastructure, bus, fuel and maintenance costs are prohibitively expensive
- safety concerns regarding handling of fuel and use in tunnels

Currently, there are no long term commercial hydrogen fuel cell buses in operation. There have been several pilot projects around the world and several countries, including the United States, are committed to making hydrogen fuel cell transit applications a reality by expanding the number of fuel cell technology vendors and maturing the technology.

CASE STUDY: TRANSPORT FOR LONDON HYDROGEN FUEL CELL PILOT

A recent trip to London afforded the research team the opportunity to learn about Transport for London's hydrogen fuel cell pilot project. Transport for London (TfL), an agency that manages the bus fleet and Underground rail operations for the Mayor of London, has introduced a pilot project that has placed eight hydrogen fueled buses into service on one route in London. This is part of a larger pilot program underway in five European cities to determine the applicability of low and zero carbon emission technology to operate a portion of local bus fleets. The deployment of hydrogen vehicles is called the Clean Hydrogen in European Cities (CHIC) project. London is working in partnership with CHIC cities to share information and experiences of operating hydrogen buses to ensure that they perform as well as they should.



TfL Hydrogen Bus
Photo: VHB

High pressure, gaseous hydrogen tanks located on the roof of the bus supply one half of the mixture needed for the fuel cell. Oxygen is taken in from the air, and which combined with hydrogen in the fuel cell, produces an electric current from the chemical reaction that releases electrons and creates water droplets and water vapor released in the air. No carbon dioxide, nitrogen oxides, or particulate matter (soot) is generated from this process, which produces zero emissions at this mobile site. Emissions potentially associated with generating the hydrogen are explained below. The electricity generated in the fuel cells powers the hybrid electric motors that propel the vehicle along with energy captured while braking as with any hybrid vehicle motor.

Benefits of hydrogen fuel coupled with a hybrid engine are many: hydrogen fuel reduces emissions contributing to improved air quality and addressing issues of climate change; the fuel cell and electric motor are quieter than diesel engines, with noise emanating

from tires, brakes, and fans only; and the electric motors provide a more comfortable ride for passengers with smooth acceleration.

The hydrogen for the London facility is generated in an industrial operation in the Netherlands, is shipped across the channel, and trucked to the maintenance facility in Leyton as liquid hydrogen. Hydrogen can be generated by electrolysis that splits water into its components of hydrogen and oxygen. The electricity used in the process can be generated using several different sources, including natural gas fired generators. When hydrogen is made using renewable energy sources such as wind power, it becomes a truly zero carbon fuel. The current pilot program, with its associated transportation impacts using tankers to move liquid hydrogen from the Netherlands is far from that ideal situation.



HYDROGEN FUELING STATION

Photo: VHB

Partners with TfL on this project are: First operating and maintaining the hydrogen buses; Wrightbus manufactures the bus body and chassis; Bluways is the system integrator, responsible for the maintenance of the new technology; Air Products provides hydrogen fuel and fueling facilities; Ballard Power Systems supplies the hydrogen fuel cells for the buses; The department for Energy and Climate Change supports the project through grant funding; and The European Commission provides funding through the Clean Hydrogen for European Cities project.

First operates the eight bus fleet out of the Lea Interchange Bus Depot in the Borough of Stratford outside the village of Leyton adjacent to the 2012 Olympic site. The garage facility was relocated from the Olympic site, is part of a larger bus fleet maintenance facility, and was built to meet the special needs of hydrogen buses.



FIRST MAINTENANCE FACILITY

Photo: VHB

Some of those special needs relate to precautions necessary to protect maintenance workers. Special detection, alarm, and ventilation requirements are provided in the two bay maintenance facility. Special training is required for maintenance workers, and additional care must be taken to be mindful of three hazards associated with these vehicles: use of flammable hydrogen gas, pressure up to 3,000 pounds per square inch in the fuel tanks, and the high voltages used in the fuel cell to hybrid motor drive train.

Since 2011 to late 2012, these buses have provided equivalent service to diesel buses, running up to 20 hours per day, and may offer potential to move to a zero emissions policy, with appropriate hydrogen generating capability, in the medium to longer term. A key to the more widespread use of hydrogen is the establishment of bus maintenance and fueling facilities in bus depots serving a greater number of routes.

SUMMARY

- Zero tailpipe emissions (besides water vapor).
- Quiet operation
- Hydrogen can be produced domestically and using renewable sources but currently at a high price
- VERY high cost of entry. Buses, fueling station, and specialized maintenance facility very expensive

- Buses are currently prototypes and not domestically produced
- Shows a significant amount of promise but currently in demonstration phase
- Long term maintenance costs and reliability unknown

LIFECYCLE COMPARISON

The lifecycle comparison of the propulsion systems reflects two key elements: Cost of ownership and operation and greenhouse gas emissions. The following sections review lifecycle costs and GHG emissions and present a cost-effectiveness analysis.

PROPULSION SYSTEM COST

The following variables presented in Exhibit 10 are cost variables taken into account in the cost analysis.

EXHIBIT 10 COST VARIABLES

Variable	Description/Assumption	Reasoning
Purchase price	The price per 40-foot bus was used	Standard bus length
# of buses	50 buses	Account for infrastructure costs; fleet acquisitions are typically not based on purchase of single unit
Annual mileage	40,000 miles per year	MBTA annual vehicle revenue miles divided by fleet size
Lifecycle	12 years	Typical MBTA assumption
Fuel Efficiency	Diesel Gallons Equivalent per mile	Industry standard when comparing alternative fuel use
Fuel Cost	\$/DGE	
Miscellaneous	Battery replacement cost Facility Conversion	Account for additional costs not included in above variables

Maintenance costs are not included in this analysis since the data found was either outdated or not presented in a consistent fashion for easy comparison. Furthermore, battery electric and hydrogen fuel cells are newly adopted and in pilot phases so maintenance data could be skewed based on the newness of the technology or the newness of the vehicles when comparing these values to more mature technologies.

Exhibit 11 presents a lifecycle cost comparison of the propulsion systems. A full list of sources and assumptions for this data is provided in the appendix. It's important to note that the purchase price for each 40-foot bus is the full retail price. In many cases, the purchase price of buses borne by the agency could be significantly lower due to federal grants and incentives toward purchasing alternative propulsion system vehicles.

EXHIBIT 11 PROPULSION SYSTEM LIFECYCLE COST COMPARISON

	Clean Diesel	CNG	Diesel-Electric Hybrid	Battery Electric	Hydrogen Fuel Cell
Purchase Price (40')	\$340,000	\$400,000	\$500,000	\$950,000	\$2,500,000
# Buses	50	50	50	50	50
Annual Mileage	40,000	40,000	40,000	40,000	40,000
Lifecycle [years]	12	12	12	12	12
DGE/Mile	4	3.6	5	23	6.8
Annual DGE Use	500,000	555,556	400,000	86,957	294,118
Fuel Cost/DGE	\$4.09	\$2.82	\$4.09	\$4.32	\$10.51
Annual Fuel Cost	\$2,045,000	\$1,567,000	\$1,636,000	\$376,000	\$3,091,000
Lifecycle Fuel Cost	\$24,540,000	\$18,804,000	\$19,632,000	\$4,512,000	\$37,092,000
Fleet Cost	\$17,000,000	\$20,000,000	\$25,000,000	\$47,500,000	\$125,000,000
Battery Replacement			\$3,000,000	\$6,000,000	\$3,000,000
Facility Conversion				\$10,000,000	\$1,500,000
Total	\$41,540,000	\$38,804,000	\$47,632,000	\$68,012,000	\$166,592,000

As shown, diesel, diesel electric hybrid and battery electric lifecycle cost are similar despite the high cost of battery-electric vehicles and the miscellaneous cost of implementing a supporting system. The relatively low cost of electricity significantly contributes to offsetting the initial capital costs. CNG presents itself as the lowest cost alternative due to the combination of relatively low capital costs and low fuel costs. Hydrogen fuel cell technology is still in its early stages and the cost of the buses (currently in prototype stages, not in production) and the cost of fueling are very high compared to the other propulsion systems. However, these costs may decrease as the technology matures. Given the MBTA's experience with CNG and infrastructure, no additional facility conversion is assumed.

GREENHOUSE GAS EMISSIONS

Using the above assumptions, the greenhouse gas emissions for the alternative propulsion fleets presented above were calculated.

EXHIBIT 12 PROPULSION SYSTEM LIFECYCLE GREENHOUSE GAS EMISSIONS

	Clean Diesel	CNG	Diesel-Electric Hybrid	Battery Electric	Hydrogen Fuel Cell
# Buses	50	50	50	50	50
Annual Mileage	40,000	40,000	40,000	40,000	40,000
Lifecycle [years]	12	12	12	12	12
Annual DGE Use	500,000	555,556	400,000	86,957	294,118
lbs CO2/gallon	27.824	23.598	27.824		Not Available
Lbs CO2/kwh				1.348	
kwh/DGE				38.081	
Tons of CO2	4,174,000	3,933,000	3,339,000	1,339,000	-

As shown, battery electric propulsion generates the least GHG emissions by nearly a factor of three when compared to clean diesel technology. The GHG emissions from battery electric propulsion are from upstream generation of electricity. Given their fuel efficiency, diesel-electric hybrids have the next lowest GHG emissions followed by CNG and clean diesel. Data for hydrogen fuel cells was not available; however, hydrogen fuel cell buses emit zero tailpipe emissions but some GHG emissions may be generated during the hydrogen production process.

COST EFFECTIVENESS

Cost effectiveness is measured based on the cost to reduce one ton of GHG emissions. Negative values represent cost savings. Diesel is used as a baseline in this analysis and all other propulsion systems are compared against it.

EXHIBIT 13 COST EFFECTIVENESS COMPARISON

	Clean Diesel	CNG	Diesel-Electric Hybrid	Battery Electric
Lifecycle Emissions (Tons CO2)	4,174,000	3,933,000	3,339,000	1,339,000
GHG Reduction (compared to diesel)		241,000	835,000	2,835,000
Lifecycle Cost (\$)	\$41,540,000	\$38,804,000	\$47,632,000	\$68,012,000
Cost Difference (compared to diesel)		-\$2,736,000	\$6,092,000	\$26,472,000
\$/Ton GHG reduced		-\$11.35	\$7.30	\$9.34

As shown, CNG is currently the most cost effective propulsion system, followed by diesel-electric hybrid and battery electric.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Several of these propulsion systems show a good deal of promise in reducing GHG emissions while either decreasing or slightly increasing lifecycle costs. The lifecycle cost analysis is sensitive to the average number of miles each vehicle travels in that the higher number of miles each bus travels, the greater weight the operation cost has on the total lifecycle cost. As such, the higher cost of diesel fuel would offset the high capital cost associated with battery-electric or hybrid buses.

Of the current propulsion systems the MBTA has in its fleet (diesel, CNG, diesel-hybrid), CNG has the lowest lifecycle cost and is the most cost-effective in reducing GHG emissions. Given that this fuel is produced domestically (relatively stable supply and price) and the MBTA has already invested so much into its CNG infrastructure, continuing to use and invest in CNG is reasonable.

Given the results of the analysis and reports from the MBTA that hybrid-electric buses present significant maintenance challenges, coupled with the news that NYC transit (an early adopter of hybrid buses) is shifting back to diesel due to maintenance issues, hybrid bus technology may need some more time to mature. Furthermore, diesel fuel prices are trending higher and these prices are not consistent due to its dependency on foreign supplies.

Battery-electric buses show a great deal of promise. While the high price of each bus and their supporting infrastructure is currently a barrier for adoption, these costs may decrease as production of the buses increases and the battery technology matures. Further, the high capital cost is offset by the operational savings in fuel cost (electricity) even at present and purchase of battery-electric buses can be subsidized through federal grants supporting alternative propulsion systems.

Hydrogen-fuel cell technology is may be a long term propulsion solution for all transportation, transit and otherwise; however, the industrial infrastructure producing hydrogen, the maturity of the transit bus technology, and the resultant cost prevent it from being a near-term solution.

RECOMMENDATIONS

The following are a series of recommendations to the MBTA to better understand whether they are capable of introducing a new propulsion system and to determine which propulsion system to introduce.

- **MBTA Bus and Maintenance Facility Master Plan** – A facilities master plan will guide the MBTA in determining the current state of the facilities, whether the current facilities need updating, understanding if additional facilities are needed, where these facilities might be located, and what would be needed to support new or expanded use of current propulsion systems.

- **Battery-Electric Pilot projects** – There are two possible pilot project opportunities the MBTA can embark on:
 - *Replacement of dual-mode articulated buses on Silver Line* – Given the age and the need to replace the DMA buses and the growing maturity of battery-electric buses, placing battery-electric buses in the Silver Line underground bus way (requiring zero-emissions) presents a good opportunity. Furthermore, using battery-electric buses eliminates the need to bring down the catenary once the bus leaves the busway, reducing delay.
 - *Replacement of trackless trolleys* – Consider replacing trackless trolleys with battery-electric buses. This would enable the buses to travel “off-route” (allowing them to based out of other maintenance facilities), replace overhead catenary wires with charging stations strengthening the character of the corridors, and potentially repurpose the North Cambridge carhouse.
- **Continue research and study of alternative propulsion systems.** The technology and cost of implementing new propulsion systems changes regularly.

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APPENDIX

COST ASSUMPTIONS AND SOURCES

	Clean Diesel	CNG	Diesel-Electric Hybrid	Battery Electric	Hydrogen Fuel Cell
Purchase Price (40')	(Richardson, 2013)	(Richardson, 2013)	(Richardson, 2013)	Proterra	(Živanović & Nikolić, 2012)
# Buses	Assumed				
Annual Mileage	Estimated based on (Massachusetts Bay Transportation Authority, 2010)				
Lifecycle [years]	Assumed based on (Massachusetts Bay Transportation Authority, 2010)				
DGE/Mile	(Richardson, 2013)	(Richardson, 2013)	(Richardson, 2013)	Proterra	(Živanović & Nikolić, 2012)
Annual DGE Use	Calculated (Annual Mileage) * (# Buses) * (DGE/Mile)				
Fuel Cost/DGE	(U.S. Department of Energy, Clean Cities, 2013)	(U.S. Department of Energy, Clean Cities, 2013)	(U.S. Department of Energy, Clean Cities, 2013)	Calculated based on (Department of Energy, 2013)	Calculated based on (Živanović & Nikolić, 2012)
Annual Fuel Cost	Calculated (Annual DGE Use) *(Fuel Cost/DGE)				
Lifecycle Fuel Cost	Calculated (Annual Fuel Cost) *(Lifecycle)				
Fleet Cost	Calculated (Purchase Price) *(# Buses)				
Battery Replacement			Single replacement \$60,000/bus	Single replacement \$120,000/bus	Single replacement \$60,000/bus
Facility Conversion				3 charging stations for 5 buses (Worcester) @ \$1 Million for 3	(Science Applications International Corporation, 2011)



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