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A Project Presented

by

AIKATERINI DELIALI

Master of Science in Civil Engineering

Department of Civil and Environmental Engineering
University of Massachusetts
Amherst, MA 01003

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Approved as to style and content by:

Eleni Christofa, Chairperson

Krystal Pollitt, Member

Sanjay Arwade
Civil and Environmental Engineering Department

ABSTRACT

Globally there have been considerable efforts of decarbonizing the transportation sector, as it has been found to be largely responsible for greenhouse gases and other air pollutants. One strategy to achieving this is the implementation of zero-emission buses in transit fleets. This paper summarizes the characteristics of three zero-emission bus technologies: 1) battery electric buses; 2) fuel cell battery electric buses; and 3) fuel cell plug-in hybrid electric buses. All of these technologies do not produce tailpipe emission and can potentially be emission-free in a well-to-wheel content, depending on the fuel source. This study aims in gathering the needed information for transitioning to zero-emission buses in transit fleets, providing insights from implementations across U.S. Data collection efforts consists of three approaches: a systematic literature review emphasizing on reports released by transit agencies and other relevant organizations, an online survey of several transit agencies that have implemented or are planning to implement zero-emission buses, and interviews with transit agency representatives. Overall, the collected information was used to identify performance measures, cost characteristics, emission savings, and fuel economy, as well as implementation approaches and refueling strategies. A comparison among the three technologies and conventional fuels (diesel, compressed natural gas) suggests that zero-emission buses outperform in fuel economy compared to conventional fleets, but their capital cost is still higher than the cost of a diesel or a compressed natural gas bus. Battery electric buses have been chosen by the majority of transit agencies and present the highest fuel efficiency among the three zero emission technologies. Challenges associated with the implementation of such vehicles and lessons learned are also summarized. Commonly admitted among all agencies is that

for a smooth transition to zero-emission fleet it is important to fully understand the technology and its requirements while starting with a small number of buses should be preferred and eventually increase the size. Further, it is critical for the staff to receive a proper training about the new technology and finally, all the involved stakeholders should maintain a good communication among them that would allow for efficient troubleshooting and information exchange.

Keywords: zero-emission technology, battery electric bus, fuel cell bus, fuel cell plug-in hybrid, transit agency

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INTRODUCTION

In the United States (US), the transportation sector is responsible for 27% of the greenhouse gas (GHG) emissions (EPA, 2015), and specifically combustion engine emissions have been found responsible for premature mortalities (Caiazzo, Ashok, Waitz, Yim, & Barrett, 2013). For almost three decades, turning to alternative fuels (compressed natural gas (CNG) or liquid natural gas (LNG)) was the main approach in addressing urban air quality degradation. However, the emergence of electric powertrain configuration enabled vehicles operating on partial or full electric mode, which does not generate any tailpipe emissions. Vehicles that fulfill this condition are known as zero-emission vehicles.

Deploying zero-emission transit buses (ZEBs) is one approach to decarbonizing the transportation sector and reducing air pollution from urban mobile sources. Due to its size and stop-and-go driving pattern, a transit bus emit more than a car (Khalighi & Christofa, 2015). In addition, due to transit fleets being a big part of vehicle fleets, they can provide an extensive blueprint for testing and refining new technologies while utilizing the benefits of being a large-scale model for fueling and management strategies. Similar as with vehicles, three types of zero-emission buses have emerged: battery electric bus (BE), fuel cell bus (FC) and fuel cell plug-in hybrid bus (FCPH). All of the three technologies deploy battery, thus they are ideal for urban environments as they benefit from regenerative braking energy that they capture from the stop-and-go driving conditions.

ZERO-EMISSION TRANSIT FLEETS IN U.S.

Motivated by their desire to reduce their carbon emissions and available funding programs, as of 2017 about 86 U.S. transit agencies were operating or planned to introduce zero-emission transit buses into their fleets. All of the three aforementioned zero-emission bus technologies have operated in U.S., but the great majority of them are battery electric buses in transit or university fleets. Since 2002, when SunLine Transit Agency put in service the first hydrogen fuel cell bus, there have been eight transit agencies to demonstrate or put in service fuel cell buses. Today, Alameda-Contra Costa Transit (AC Transit) and SunLine Transit Agency in California and Stark Area Regional Transit Authority (SARTA) in Ohio are the main fuel cell bus operators in the U.S. Their fleets consist of approximately 10 to 13 buses. As for fuel cell plug-in hybrid buses, there have been only seven demonstrations in the U.S., but most of them were demonstrations run by Proterra. Only University of Delaware is operating two buses of this type (as of October 2017).

Currently active or proposed implementations are shown in Figure 1. Table 1 presents a timeline of zero-emission transit fleets, for which information is presented in this study. The oldest implementation is 1991 for Santa Barbara BEBs, however, we show data from 2002 and on. It can be seen that while BE buses initially implemented in the early 1990s, fleets started expanding from 2010. Fuel cell technologies have recently started expanding, while smaller fleets (1 to 3 buses) were initially tested.

The National Renewable Energy Laboratory (NREL) has been compiling data to assess the operation of FC and FCPH bus implementations, as well as two BE fleets, Foothill Transit and King County Metro, has introduced the index Technology Readiness Level

(TRL). The purpose of this index is to quantify the maturity of each technology, indicating whether it is ready to be fully commercialized (stage 9) or being in an initial research stage (stage 1). As of November 2017, NREL denotes active BEB fleets in U.S. as having a TRL of 7 while FCB have a TRL between 7 to 8 (Leslie Eudy, Prohaska, et al., 2017a; Leslie Eudy & Post, 2017). Therefore, even if the majority of agencies have chosen battery electric buses, it does not mean that this technology is outperforming the others. In reality, outside of U.S. the fuel cell bus market in largely developing.

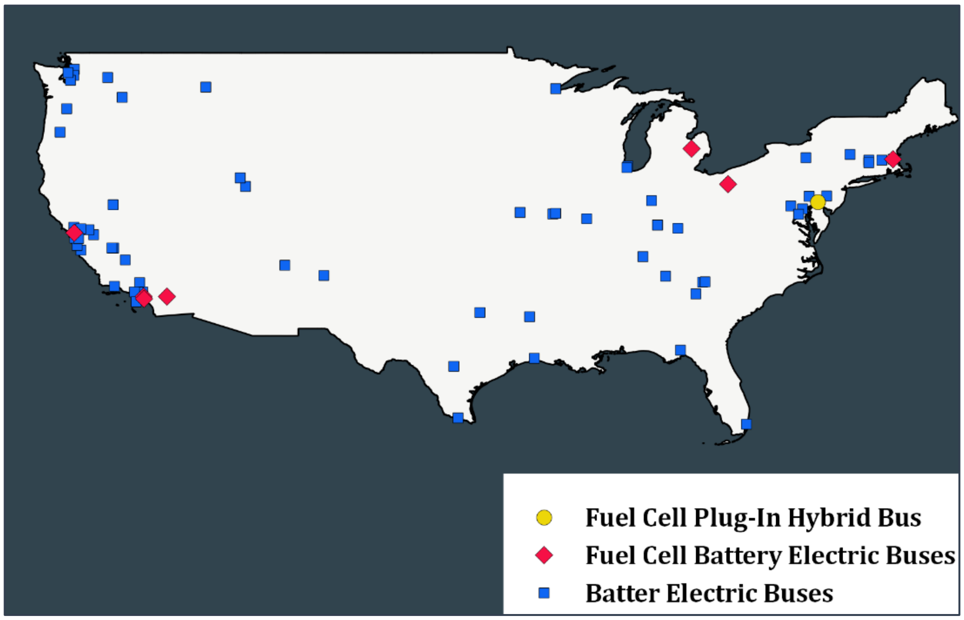

Figure 1- Overview of U.S. transit agencies currently operating or having proposed plans to incorporate ZEBs in their fleet (as of 2017).

Table 1-Timeline of zero-emission transit fleets across U.S.

Agency	Buses	2002	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
BATTERY ELECTRIC BUSES																	
Antelope Valley Transit Authority (CA)	41																
Capital District Transportation Authority (NY)	1																
Central Contra Costa Transit Authority (CA)	8																
Chicago Transit Authority (IL)	6																
Clemson Area Transit (SC)	10																
Dallas Area Rapid Transit (TX)	7																
Foothill Transit (CA)	31																
Indianapolis Public Transportation Corporation (IN)	21																
King County Metro (WA)	84																
Lexington-Fayette Urban County (KY)	6																
Los Angeles County Transportation Authority (CA)	5																
Pioneer Valley Transit Authority (MA)	3																
Regional Transportation Commission Washoe (NV)	4																
Santa Barbara MTD (CA)	30	Active since 1991															
Shreveport Area Transit (LA)	5																
Southern Pennsylvania Transportation Authority (PA)	25																
Springfield Area Transit Company (MA)	3																
Star Metro Transit (FL)	6																
Stanford University (CA)	39																
University of California Los Angeles (CA)	2																
Utah Transit Authority (UT)	6																
VIA Metropolitan Transit (TX)	3																
Washington Metropolitan Area Transit Authority (DC)	1																
Worcester Regional Transit Authority (MA)	7																

Agency	Buses	2002	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
FUEL CELL BUSES																	
Santa Clara VTA (CA)	3																
FUEL CELL BATTERY ELECTRIC BUSES																	
Alameda Contra Costa Transit (AC Transit) (CA)	3																
	13												Stage 1: 12 FCBE buses				Stage 2: +1
Connecticut Transit CTTRANSIT (CT)	1																
	4																
Flint Mass Transportation Authority (MI)	1																
	1																
Massachusetts Bay Transportation Authority (MBTA) (MA)	1																
Orange County Transportation Authority (OCTA) (CA)	1																
Stark Area Regional Transit Authority and Ohio State University (SARTA) (OH)	11																
SunLine Transit Authority (CA)	1																
	1																
	1																
	9											Stage 1: 1 AFCB			Stage 2: 3 AFCB		St.3: +5
University of California Irvine (UCI) (CA)	1																

Agency	Buses	2002	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
FUEL CELL HYBRID PLUG-IN BUSES																	
Birmingham-Jefferson County Transit Authority (AL)	1													■	■	■	
City of Burbank (CA)	1									■	■						
CapMetro Transti Authority (TX)	1														■		
Central Midlands Transit (SC)	1									■							
Flint Mass Transportation Authority (MI)	1															■	■
	2						■	■	■	■	■	■	■	■	■	■	■
University of Texas (TX)	1						■	■									

This study summarizes the characteristics of three zero-emission bus technologies (battery electric, fuel cell, and fuel cell plug-in hybrid buses) focusing on information obtained from U.S. transit fleet implementations. Data collection efforts consists of three approaches: a systematic literature review emphasizing on reports released by transit agencies and other relevant organizations, an online survey of several transit agencies that have implemented or are planning to implement zero-emission buses, and interviews with transit agency representatives.

The three following sections are dedicated to each one of the three technologies reporting refueling strategies, performance measures and cost characteristics, and lessons learned. Next, we discuss the existing challenges of the three technologies and present a comparison among them. Last section contains the conclusions of this study.

BATTERY ELECTRIC BUSES

Battery electric buses have an onboard battery system that is operated using electric power. They generate no tank-to-wheel emissions but atmospheric pollutant releases are associated with generation of the electricity used to recharge the onboard battery (Lowe et al., 2009). Battery configuration varies depended on the charging strategy, which may be plug-in slow charging or on-route fast charging.

The active battery electric bus manufacturers in U.S. involve an array of companies: Proterra, Build Your Dreams, Complete Coach Works, and New Flyer.

Charging strategies and facilities

Battery charging is critical for battery electric buses implementations. It affects the driving range of the bus and in turn, bus routing and charging infrastructure placement and cost. There are three charging approaches: plug-in charging, conductive charging, and inductive charging

(Figure 2). Depending on the choice of the transit system for a charging strategy, the buses are configured with batteries specific to that chosen charging strategy. Half of the transit agencies who reported on their charging method proclaimed the use of depot, overnight charging.

Plug-in charging

Plug-in charging is typically scheduled during extended periods of non-operation time while the battery electric buses are stationed at their home depot. Charging during the night is referred to as overnight charging. Plug-in charging occurs by physically plugging in the charger to a charging port on the battery electric bus. The charging occurs at a lower voltage (40 to 120 kW), and therefore it requires longer charging times compared to higher-voltage conductive or inductive charging (Hanlin, Reddaway, & Lane, 2018). Overnight charging requires a large battery to be installed on the bus to account for the extended intervals between charge times. Battery electric buses are typically fit with a battery that can operate for a range of up to 200 miles and be charged over a two- to four-hour period (Mahmoud, Garnett, Ferguson, & Kanaroglou, 2016). In locations with decreased overnight (off-peak) electricity costs compared to daytime usage rates, overnight charging can have cost-saving effects. A potential drawback of plug-in overnight charging is that when battery electric buses are implemented on long routes, there might be a need for buses to return to the depot during the day. As a result, additional buses might need to be purchased to cover part of the schedule while other buses are charging, which could add to the transit agency cost (Li, 2016).

Two technological advancements have addressed low ranges and long charging times: the introduction of lithium-based batteries that improved battery capacity and the development of fast charging techniques, which enable on-route charging (Li, 2016). These technological improvements have motivated battery electric buses commercialization and deployment in larger scales.

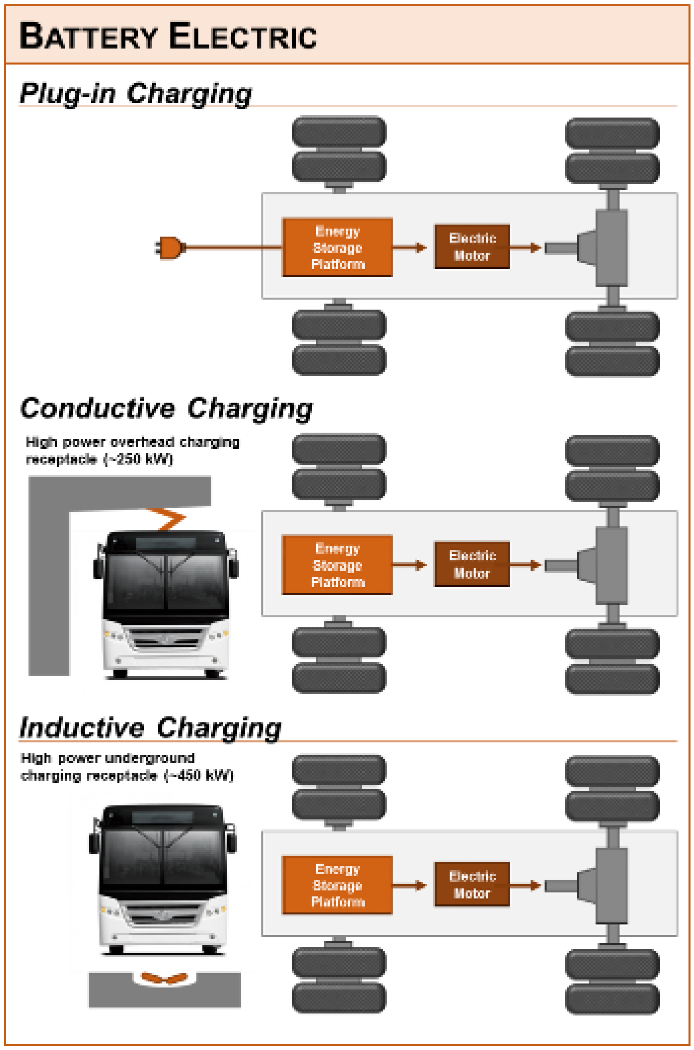

Figure 2-Overview of battery electric bus charging methods

Conductive and inductive charging

Conductive charging uses a power of on average 250 kW across bus manufacturers, allowing for a range of 20 to 30 miles on a 5 to 20-minute charge. Inductive charging uses a higher charging power (400 to 500 kW), such that a 15-second charge can add 12 miles (Mahmoud et al., 2016). As both methods use high charging power, the size of the battery can be scaled down compared to the plug-in charging design. Smaller batteries have positive implications on energy consumption and emissions. Facilities for conductive and inductive charging of battery electric buses can be costly because of the need to provide higher power in a short period of time and also additional infrastructure is required. In addition, they require higher demand for energy during operation as compared to overnight plug-in electric bus charging (Lowe et al., 2009). On-route charging facilities are commonly installed at transit centres, e.g. intermodal transit hubs, which are locations own by the agency.

Typical route assignment/scheduling

There are several considerations for deciding on the appropriate routes for battery electric buses including driving range under one charge, availability of charging infrastructure and space for it, as well as the impact of charging voltage and therefore, charging time on scheduling. The main consideration for this type of technology is the location of the charging infrastructure. If the buses were to be charged on-route, then the buses can only be deployed where the routes have been electrified and appropriate charging infrastructure is available. Enough chargers should be built on the way so that the range of the bus is not exceeded. Furthermore, charging time must be built into the schedule to prevent delays and range anxiety. Similarly, for buses that are charged at the depot, the length of the route cannot exceed the effective range of the bus, while taking into consideration the terrain and the use of an air conditioner or a heater. Moreover, transit agencies tend to prefer to put battery electric buses on routes that have high visibility.

There are modeling and simulation tools available that can determine the effectiveness of buses on certain routes while inputting various terrain, weather, and operational conditions. Transit agencies have validated such models by stating that the real data matched the simulated data very well.

Most of the participant agencies reported that they operate their battery electric buses five days a week, and some during the whole week. The distance traveled every year by battery electric buses is between 5,300 and 40,000 miles. The routes that the buses are put on vary in length from 3 to 5 miles per trip with stops every 0.1 to 0.2 miles, to 18 miles per trip with stops every 5.3 to 8.3 miles. Overall, the number of stops varies a lot (from 10 to 64), and is dependent on the specific route. There is no consensus on the distances between stops or from the first/last stop to the depot, but the battery electric bus runs (from first stop to last stop) usually take between 30 to 60 minutes, where the lowest limit was reported by Stanford University and 60 minutes last the trips at LACMTA and PVTA.

In-Service performance

Performance of battery electric buses is discussed in terms of fuel efficiency, ability to operate as expected and emission savings. From the interviewed agencies it was been reported that BE buses performance is affected by seasonal changes. Specifically, several issues regarding the driving range, fuel economy and bus start up time have been associated with cold weather. Worcester Regional Transportation Authority (WRTA) in Massachusetts found that the bus could operate for less miles and the fuel efficiency dropped significantly during winter. Start-up time might last longer and the bus cannot be heated in comfortable level.

Fuel economy

Battery electric buses are at least two times more fuel-efficient compared to conventional fuel buses (diesel and CNG), reporting a range of 8 to 29 miles per diesel gallon equivalent (mpdge) (Table 2). The lower value has been reported by WRTA and is rather extreme as the average fuel economy is about 17 mpdge.

Table 2- Fuel Economy and fuel cost per mile for battery electric buses

Transit Agency	Fuel Economy (mpdge)		Fuel Cost per Mile ($/mile)	
	Battery Electric	Conventional*	Battery Electric	Conventional*
Clemson Area Transit (SC)	17	3.9	0.26	0.66
Foothill Transit (CA)	17.5	NR	0.39	NR
Indianapolis Public Transit	NR	5	NR	NR
King County Metro (WA)	16.7	5.4	0.18	0.44
Los Angeles MTA (CA)	12.1	2.7	NR	NR
Regional Transportation Commission Washoe (NV)	17.0–29.0	3.8	NR	NR
Santa Barbara MTD (CA)	27.32	4	NR	NR
StarMetro (FL)	NR	NR	0.7262	0.9
Worcester Regional Transit Authority (MA)	8 *–23	5-Apr	0.4	0.6

Availability and reliability

Bus performance could be evaluated as function of: availability, which is the percentage of days the buses are available out of days that buses are planned for operation, and reliability, which is defined as the miles between road calls or miles between failures. Failure is a situation where the bus has to be replaced or causes a significant delay until it is fixed. Specifically, Foothill Transit and King County Metro (Table 3) battery electric fleets have an availability of 84-90%, which complies with the target of 85% that transit agencies set (Eudy & Post, 2017). Lower availability has been mainly attributed to maintenance needs and issues with the electric motor (Eudy &

Jeffers, 2017). Reliability was found to be higher for the propulsion system (between 6,488 and 25,078 miles) and lower for the bus itself, which seemed to have most of its problems ranging from 2,433 to 9,331 miles between road calls. Issues related to the bus propulsion system are attributed to transmission system, batteries and electric drive, while bus-related issues refer to bus parts such as brakes, suspension, steering, and tires.

Table 3- Performance measures for battery electric buses

Transit Agency	Demo. Period	Fleet Size	Average Monthly Mileage (miles per bus)	Average Speed (mph)	Availability (%)	Miles Between Road Calls (MBRC) (miles)	Fuel Economy (mpdge)	Fuel cost ($/mile)	Maintenance cost ($/mile)
Foothill Transit (CA)	2014-2016	12	2333-2,456	8.4	90	Bus: 6,180-9,331 Propulsion: 25,078	17.4-17.5	0.37-0.52	0.16-0.21
King County Metro (WA)	2016-2017	3	2,467	10.6	84–98	Bus: 2,433 Propulsion: 6,488	16.7	0.50-0.58	NR

Emission savings

Life cycle assessment has been evaluated in order to account for the emissions related to the electricity generation process. Assuming a 12-year lifetime, a battery electric bus is associated with 543 to 1,004 tons of carbon dioxide equivalent (CO_2-eq), as compared to 1,446 to 2,284 tons of CO_2-eq for diesel bus (Ercan & Tatari, 2015). The ranges can be attributed to different methods for electricity production (solar panels and a mix of grid scenarios), driving cycles, fluctuation in fuel price, manufacturing process and supply chain characteristics. Diesel buses have an estimated range of 1,700 to 3,900 g CO_2-eq/mile for a 20-year time horizon and 2,200 to 3,750 g CO_2-eq/mile for a 100-year time horizon, depending on the testing cycle used (Lowell, 2011). The only transit agency that reported emission savings was Central Contra Costa Transit Authority. The operation of battery electric buses reduced the total emissions by 154 tons of CO_2 per year as well as the annual diesel fuel purchases by 13,954 gallons (Muzzini & Storer, 2016).

Clemson Area Transit also reported that between September 2014 and March 2016, the agency avoided consumption of 60,000 gallons of diesel due to the addition of battery electric buses. This also resulted to an amount of CO_2 savings equivalent to the amount of carbon sequestered by 304 acres of U.S. forests in one year (Connell, 2016).

Based on e-Grid database (2014), the CO_2-eq emission factor for the New England region was about 577 lbs/MWh (U.S. Environmental Protection Agency, 2017), and for Massachusetts the CO_2 emission factor for electricity retailers is estimated to be 654 lbs/MWh (Massachusetts Department of Environmental Protection, 2016), with an average value for the U.S. of about 1,477 lbs/MWh (U.S. Environmental Protection Agency, 2017). These values depend on the energy source used to generate electricity. If the energy source for charging the bus battery originates from renewables such as solar or wind, it is feasible further emission reductions could be achieved for this electric bus design.

Costs

Procurement cost

Battery electric bus procurement costs ranged between $537,000 and $950,000, depending on bus and battery size that is determined by the charging infrastructure. Note that the $350,000 cost reported by Santa Barbara Metropolitan Transit District was the cost in 2000 when it purchased those vehicles. Decreased vehicle procurement costs have been reported for the conductive charged design as compared to the plug-in charged bus design because of the smaller onboard battery package (Heroy-Rogalski et al., 2015). In contrast, the infrastructure costs for the plug-in charged bus types were significantly lower as compared to those of buses using the conductive charging approach. Other costs associated with the implementations were related to charging and retrofitting of batteries.

Infrastructure cost

Regarding the infrastructure, the cost is mainly determined by the charging method. Plug-in charging facilities are placed at the bus depot or maintenance area; several agencies have received funds to build charging infrastructure. The overnight approach has been found to be about $50,000, ten times less that the on-route facilities (Hanlin et al., 2018). Overall, the data for infrastructure costs was rather limited, with only Santa Barbara Metropolitan Transit District reporting that the cost for a new transformer, switchgear, and charging infrastructure (more than 14 plug-in chargers) was $3 million.

Operation cost

The reported U.S. battery electric bus implementation electricity charges range from $0.07 to $0.30 per kWh and vary widely with the level of demand for the grid, the time of the day and the period of the year. The per mile cost for the country was found to be from $0.15 to $0.89 (Hanlin et al., 2018). Estimated energy costs for California, the state with the most implementations of BE buses, vary from $0.11 to $0.20/kWh for depot charging and $0.15 to $0.25/kWh for on-route charging (California Air Resources Board, 2017). Other studies have reported energy costs for fast charging approaches to be $0.29/mile ($0.18/km) (Li, 2016) assuming an electricity cost of transportation of about $0.10/kWh as provided by the Energy Information Administration (U.S. Energy Information Administration, 2018). Energy costs for overnight charging in the U.S. have been estimated to be $0.20/mile ($0.12/km) (Li, 2016).

The operating cost (i.e., fuel/energy cost) per mile for battery electric buses ($0.18 to 0.72/mile) is comparable to that of diesel buses ($0.18 to 0.90/mile) (Table 2). Batteries for transit buses have been seen to improve over time within several agencies. In addition, it was found that implementations that accounted for the differences between different routes and were tailored to the specific needs of each route may be less costly.

Regarding staff training costs, only the Los Angeles County Metropolitan Transportation Authority (LACMTA) provided a value of $100,000, which was spent prior to the implementation of its battery electric buses. In most cases, the cost of training was included in the cost of the battery electric buses reported.

Maintenance cost

The maintenance costs of battery electric buses are dependent on the availability of parts from the manufacturer and whether the bus warranty is under. Battery electric buses have extended maintenance intervals, fewer fluids, fewer moving parts (about 30% less), and decreased emissions as compared to conventional diesel buses (Center for Transportation and the Environnment, 2017). Battery electric buses have regenerative braking systems, which reduce brake wear and expensive brake repair. For example, the maintenance cost per mile for battery electric buses was reported as 11% lower than that of CNG buses (Eudy, Prohaska, et al., 2016) and, on average, 80% lower than that of diesel buses (Mahmoud et al., 2016). When comparing between different battery electric buses, maintenance costs are reported to be on average $0.72/mile (range $0.16 to $1.00/mile) in contrast to an average of $1.34/mile for conventional buses (range $0.22 to $3.00/mile) (Table 4). The range in costs is attributable to the variability in the items included in total maintenance costs across agencies.

In most cases, maintenance is done in-house. In Massachusetts, Pioneer Valley Transit Authority and Worcester Regional Transit Authority have reported that it is beneficial having a maintenance technician from the manufacturing company works on a full-time basis for the transit agency. Another option is to provide maintenance for the fleet through contracts with private firms. Foothill Transit reported its maintenance labor rate was $50 per hour for Proterra technicians to repair buses that are no longer under warranty. Eventually the agency started providing maintenance by its own staff (Eudy, Prohaska, Kelly, & Post, 2014).

The annual cost for maintenance of battery electric buses has been reported by Foothill Transit to average above $9,000 per year, with an average total cost of $0.16/mile. The majority of maintenance costs for battery electric buses can be attributed to preventative maintenance, compared to a majority of costs being propulsion-related for CNG buses (Eudy, Prohaska, et al., 2017b). A way to reduce maintenance cost is to ensure increased monitoring of systems that may reduce any malfunctions associated with overheating or voltage levels. Many of the battery electric buses provide data from the vehicle telemetry, and such data can be transmitted to the manufacturer to limit maintenance time.

The operational and maintenance costs for the charging infrastructure are estimated to be $500/year for a depot charger and $13,000/year for an on-route charger, as reported by CARB (California Air Resources Board, 2017).

Table 4- Maintenance cost for battery electric buses

Transit Agency	Maintenance cost ($/mile/bus)	
	Battery Electric	Conventional
Alameda Contra Costa Transit	NR	1.15

Foothill Transit	0.16-0.21	0.22
Los Angeles County Metropolitan Transportation Authority	>1.00	3
Santa Barbara Metropolitan Transit District	>1.00	<1.00

Cost projection

Cost projections made by CARB for BE buses (Figure 3), show a decrease in cost of battery electric buses regardless of the charging method over the next 2 years followed by a general increase. The capital cost of the buses will return to their 2016 value for in-depot charging ($770,000) and on-route charging ($750,000) value in about 11 years. At the same time capital costs for diesel hybrid buses is expected to increase at an annual rate of 2.35%. Inflation or any discount from the manufacturer have not been taken into account (California Air Resources Board, 2016).

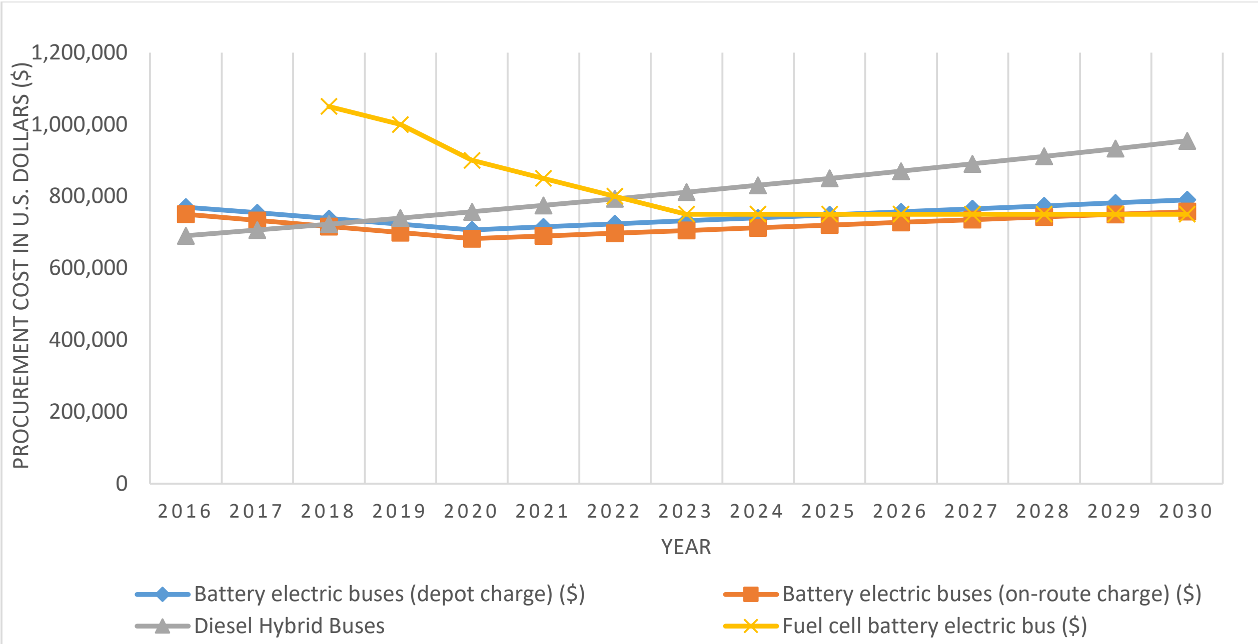

Figure 3- Procurement cost projection for battery electric, fuel cell battery electric, and diesel buses (California Air Resources Board, 2016)

FUEL CELL BATTERY ELECTRIC BUSES

Fuel cell buses design

A fuel cell is an electrochemical reactor that produces electricity after a chemical reaction. Buses store hydrogen on-board in storage tanks and it is supplied to the fuel cell to produce electricity which powers the vehicle. Water is the only by-product, making a hydrogen fuel cell system a zero emission technology, in contrast with other fuels (i.e. methanol). Two power configurations exist; in the first design, buses directly use the power generated by the fuel cell (i.e., direct-use). The second design incorporates a storage platform to capture excess energy into the powertrain (Figure 4). These buses are known as hydrogen fuel cell battery electric buses. The storage platform on these buses typically includes batteries, super-capacitors, or a combination of these storage options. The need for energy storage was integrated into fuel cell vehicles when high hydrogen costs made operation of this zero emission technology economically unsustainable

(Lukic, Jian Cao, Bansal, Rodriguez, & Emadi, 2008). Energy storage device is capable of capturing energy from regenerative braking to buffer peak power loads. FC buses can be either fuel cell-dominant or battery-dominant. In the fuel cell-dominant design, all of the bus's power comes directly from the fuel cell. The battery provides transient power when required. In contrast, in a battery-dominant configuration, the battery is the primary energy source for propulsion. The fuel cell in this case produces electricity for the battery, to extend the driving range.

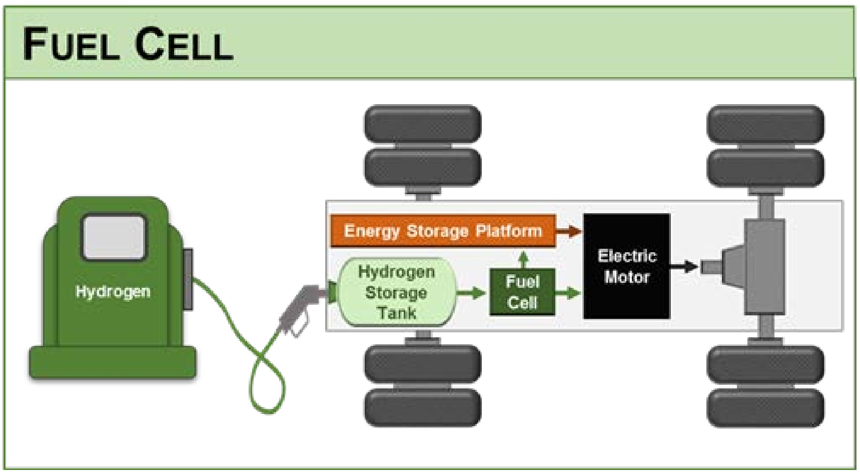

Figure 4-Overview of the powertrain in hydrogen fuel cell buses

In U.S. fleets there have been tested several fuel cell battery electric buses, some of them have been excluded from the market. The first generation was tested between 2006-2010 in three sites: AC Transit, Sunline and CTTRANSIT (Connecticut Transit). The current AC Transit fleet is the second generation of this model, in the sense that the same manufacturers improved their initial design. Later on a U.S.-based market was created and has been launching FCBE buses to SunLine, MBTA, SARTA, OCTA and UC Irvine.

Refueling Strategies and Facilities

Fuel cell buses store hydrogen in tanks positioned on the roof of the bus. Production facilities can either be located on-site at a bus depot location or off-site with hydrogen delivered to a storage site at the bus depot. Each method has advantages that vary by geographical location of the transit bus fleet and by the relative size of the fueling station or network of stations.

Two of the largest fuel cell fleets in U.S., AC Transit and SARTA have the hydrogen being delivered to them in liquid form, while SunLine Transit produces hydrogen on-site with natural gas reformer. Steam methane reformer is the most common way for on-site hydrogen production in the U.S. given the well-developed natural gas infrastructure. It should be noted that transport costs significantly affects the price of the hydrogen fuel The total price of fueling fuel cell buses with hydrogen depends on the delivery method (pipeline, trucks), the state of the hydrogen (e.g. gaseous or liquid), and the demand for hydrogen at each location (Langford & Cherry, 2012) This is why, among the interview and studied agencies we have not find a pattern in the reported hydrogen prices; the range is 4.5 to 23.5 ($/kg).

The pressure of the supply line can be varied to modulate the fueling rate, which can be either “slow” or “fast”. The reported times vary from 6 to 24 minutes.

Typical route assignments/scheduling

Current fuel cell bus implementations consist of a small number of buses. The main consideration for fuel cell buses in this regard is that route assignments are limited by the need for approvals from routes of cities that the bus will pass through. One desirable aspect in choosing a route is that like battery electric buses, assigning the buses routes in which there is high visibility by pedestrians promotes the technology. Moreover, since fuel cell buses only need to refuel usually once a day at the hydrogen fueling station, this bus is not limited by driving range. Despite the increased flexibility in driving routes, some agencies have still tested their fuel cell buses on routes with less than ideal conditions, such as a route having a hilly terrain. University of California Irvine (UCI) and SARTA provided information regarding the routine and scheduling. The main difference between these two entities is that UCI has one bus that operates on the university's campus, while SARTA has eleven buses with a wide range of routes. SARTA serves a much denser network in terms of bus stops location, but both buses on both agencies complete similar daily mileage and one cycle lasts from 30 to 40 minutes.

In-service performance

Both AC Transit and SunLine had implemented in the past (before 2010) other bus designs that have been removed and replaced with improved ones. As these agencies have been engaged to fuel cell buses for a relatively long time compared to more recent implementations, e.g. MBTA, UCI, and Orange County Transportation Authority (OCTA), the corresponding performance data has shown improvement.

Overall fuel cell buses have been tested in multiple environments with respect to climate and the service area. Connecticut implementations wanted to test the buses performance in cold and snowy weather as this might cause the water in the fuel cell to freeze or other issues to propulsion system due to cold climate. While these were the concerns, agencies have not reported any relevant issues.

Fuel economy

The fuel economy for a fuel cell bus ranges from 4.53 to 11.5 mpdge (with an average of 6.3 mpdge), compared to a range of 3.8 to 4.28 mpg reported for conventional diesel buses, and 3.11 to 3.33 mpg reported for CNG buses for the same transit agencies (Table 5).

Table 5- Fuel Economy and fuel cost per mile for fuel cell buses

Transit Agency (Program)	Fuel Economy (mpdge)		Fuel Cost per Mile ($/mile)	
	Fuel Cell	Conventional*	Fuel Cell	Conventional*
AC Transit (ZEBA)	6.06–7.43	3.85–4.24	1.30–1.58	0.44
SunLine (AFCB)	6.20–7.83	3.11–3.32 (CNG)	1.35	0.34 (CNG)
UCI (AFCB)	5–5.82	NR	NR	NR

*NR: Not Reported; * Refers to diesel (unless otherwise mentioned)*

Availability and reliability

Since 2003 that the first hydrogen fuel cell bus was deployed in U.S., the bus configuration as well as the fuel cell and the battery have been improved. At the same time, various parties involved in buses implementation became more familiar with this bus type, fuel cell fleets show improvement in their performance. Availability has improved from 44-75% to 61-90% for ongoing implementations, while miles between roadcalls have shown an increase in the current fleets compared to the older ones (2006-2010). Before 2010, the monthly average mileage per bus ranged between 900 and 1,700, while later, the range has been extended to between 1,000 and 3,000 miles. The average monthly mileage for diesel buses is between 3,300 and 4,800 miles. MBRC have also improved with time. (Table 6).

Table 6- Performance measures for fuel cell buses

Transit Agency (Program)	Demo. Period	Fleet Size	Average Monthly Mileage (miles per bus)	Average Speed (mph)	Availability (%)	Miles Between Road Calls (MBRC) (miles)	Fuel Economy (mpdge)	Fuel cost ($/mile)	Maintenance cost ($/mile)
AC Transit (ZEBA) (CA)	2010-2016	13	1,089-2,646	12.1	67-82	Bus: 4,708-5,007 Propulsion: 7,500-9,169 Fuel cell: 15,000-32,771	6.06-7.34	1.30–1.58	0.86–1.31

MBTA (MA)	2016-2017	1	601	8.3	NR	NR	4.86	NR	NR
OCTA (CA)	2016-2017	1	1,001	13.4	36-42	Bus: 1,300 Propulsion: 1,500 Fuel Cell: 6,000-8,488	7.59	NR	NR
SunLine Transit (AFCB) (CA)	2011-2016	5	1,676-3,028	14.8	61-77	Bus: 1,692-6,335 Propulsion: 3,383-8,025 Fuel Cell: 7,894-28,000	6.2-7.83	1.35	0.39–0.54
UC Irvine (CA)	2016-2017	1	2,300	NR	88-90	Bus: 4,170 Propulsion: 5,210 Fuel Cell: 10,425	5-5.82	NR	0.47

Emission savings

For tank-to-wheel emissions, fuel cell bus designs are zero-emission technologies. Water is the only by-product of the process used to convert hydrogen to electricity in the fuel cell onboard the bus. However, the processes of producing hydrogen offsite and transporting it to the bus depot fueling station are sources of atmospheric pollutants, including carbon dioxide (CO_2), nitrogen oxides (NO_x), volatile organic compounds, methane, and sulfur dioxide (McKenzie & Durango-Cohen, 2012). As with battery electric buses, a life cycle assessment can be used to estimate the true emission profile of this fuel cell technology. Estimates from existing studies report life cycle GHG emissions of 1,500 to 2,000 g/mile for fuel cell buses (using steam reforming of natural gas for hydrogen production) (Lajunen & Lipman, 2016), which is much lower than the corresponding value for diesel buses and comparable to the estimate for battery electric buses. Studies using Lifecycle Emissions Model (LEM) show fuel cycle GHG emissions that range from 77 to 264 g/mile and fuel and vehicle life cycle GHG emissions that range from 155 to 360 g/mile, depending on fuel and fuel feedstock used for hydrogen production (Lipman & Delucchi, 2006). A study that used the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model reports much higher well-to-tank emissions for fuel cell buses compared to battery electric and conventional buses assuming 100% steam reforming of natural gas from North America (Lajunen & Lipman, 2016). No transit agency has reported estimates of any emissions associated with fuel cell bus operations.

Costs

Procurement cost

Currently the cost of fuel cell buses is about $1.8 million, almost double of that of battery electric buses. There has been a significant improvement in the cost compared to before 2008, when it was more than $3 million. The main cost contributor is the fuel cell stack; technological progress has helped making it smaller and more efficient. Further, the U.S. Department of Energy has studied the benefits of the economies of scale regarding the procurement of fuel cell buses and in particular the fuel cell component. It was shown that a five-time increase of fuel cell component production can result in a decrease of almost 50% in their individual cost. Therefore, mass production of these buses in the future is expected to positively affect the prices (Lajunen & Lipman, 2016). The cost of procuring fuel cell buses is also expected to keep decreasing in the next 10 years as fuel cell technology matures and becomes less expensive

Infrastructure cost

All of the transit agencies needed to build new or expand their existing depot facilities in order to accommodate the fueling and maintenance facilities for fuel cell buses. Available data does not seem to agree on a specific required cost for these modifications. Different bus operators had to build new facilities or expand their current ones, making it hard to make infrastructure cost estimations due to the variability in capacity, types of infrastructure, e.g., whether it is a fueling station or also a hydrogen production facility. Available data exist for AC Transit that show that a new hydrogen fueling station with fueling capability of 600 kg of hydrogen per day for both cars and buses costs about $10 million (Eudy, Post, Gikakis, Eudy, & Post, 2014). UCI reported a value of $287,694 per station for a hydrogen refueling station expansion, and SARTA reported a cost of $1.8 million as the infrastructure cost of building a new hydrogen production fueling station with capacity of 300 kg per day (Sokolsky, Tomic, & Gallo, 2016).

Operation cost

The price of hydrogen fuel is much higher compared to diesel ones, with a wide range of $4.52-23.5/kg across different sites with the lowest and highest reported for SARTA and SunLine, respectively. On average the hydrogen cost is about $9 per kg. The range could be attributed to consumption rates related to fleet size: UCI ($12.99/kg) implemented only one bus and SARTA implemented eleven buses. In fact, the price of hydrogen fuel at UCI was a major drawback in the fuel cell bus implementations and motivated the transition to battery electric, where buses are able to use the university's micro grid for recharging. SunLine experienced a damage in its on-site fueling facility that forced the agency to deliver hydrogen instead of producing, which was much costly (Eudy, Post, & Jeffers, 2017).

The per-mile cost of operating a fuel cell bus, i.e., fuel cost, ($1.1 to $2.91 per mile) is higher than that of conventional bus technologies ($0.44 to $0.69 for diesel and $0.29 to $0.61 for CNG) reported for the same transit agencies.

Maintenance cost

Maintenance costs are low for scheduled operations ($0.11-0.27/mile), however, unscheduled maintenance results in additional costs ($0.45-0.98/mile) (Eudy & Post, 2017). Variability in this cost can be attributed to the individual problems each demonstration was facing and also, whether the buses were under warranty. In the latter case, the reported total maintenance cost is very low (about $0.40/mile) (Table 7). The 2016 and the ultimate targets set by FTA for per-mile maintenance cost, which includes both scheduled and unscheduled, are $0.75 and $0.40 per mile, respectively (Leslie Eudy & Post, 2017). The trend has not stabilized yet, since there are data periods in which transit agencies are close to the targets, but there are also data periods in which they are below the targets. Overall, transit agencies reported a maintenance cost of $0.39 to $1.31 per mile.

Table 7-Maintenance cost for fuel cell buses

Transit Agency	**Bus Maintenance Costs ($/mile/bus)**	
	Fuel Cell	**Conventional**
AC Transit (ZEBA)	0.86–1.31	0.25–0.68
SunLine (AFCB)	0.39–0.54	
University of California Irvine	0.47	2.55

Cost projection

Figure 3 reflects the capital cost projections made by CARB for fuel cell buses without accounting for inflation or any decided upon discount from the manufacturer (California Air Resources Board, 2016). A general decrease in the cost of the buses over the next 5 years followed by a stabilization in price at $750,000 is predicted. The hydrogen prices will decrease over the next couple of years with a set goal of $4/kg by U.S. DOE in 2020 (Satyapal, 2016).

FUEL CELL HYBRID PLUG-IN BUSES

Fuel cell plug-in hybrid bus design

Fuel cell plug-in hybrid (FCPH) buses are similar to fuel cell buses with respect to their powertrain configuration: both contain onboard batteries and fuel cells. The batteries on FCPH bus can be charged through a hydrogen fuel cell, regenerative brakes, or through a connection to an external electrical source. It is noteworthy that the fuel cell on FCHBs has been integrated into the powertrain as auxiliary power unit to extend driving range, enabling the use of smaller size fuel cells compared to those used on 6 FCBE buses.

The need for hybridized fuel cell buses emerged when it was realized that increasing hydrogen costs were decreasing the economic viability of this electric vehicle design (de Miranda, Carreira, Icardi, & Nunes, 2017). This zero-emission bus type is not as popular as the two previous ones and it is mostly on an experimental stage. Two bus manufacturers have been involved with this design, Proterra and Ebus partnered with several transit agencies to launch its bus. Although most interviewed and surveyed agencies reported being satisfied with their zero-emission fleet, one agency that demonstrated a Proterra FCPH bus was rather disappointed with it. Due to the small number of demonstration sites and short time period, data is rather limited for fuel cell plug-in hybrid buses in the US.

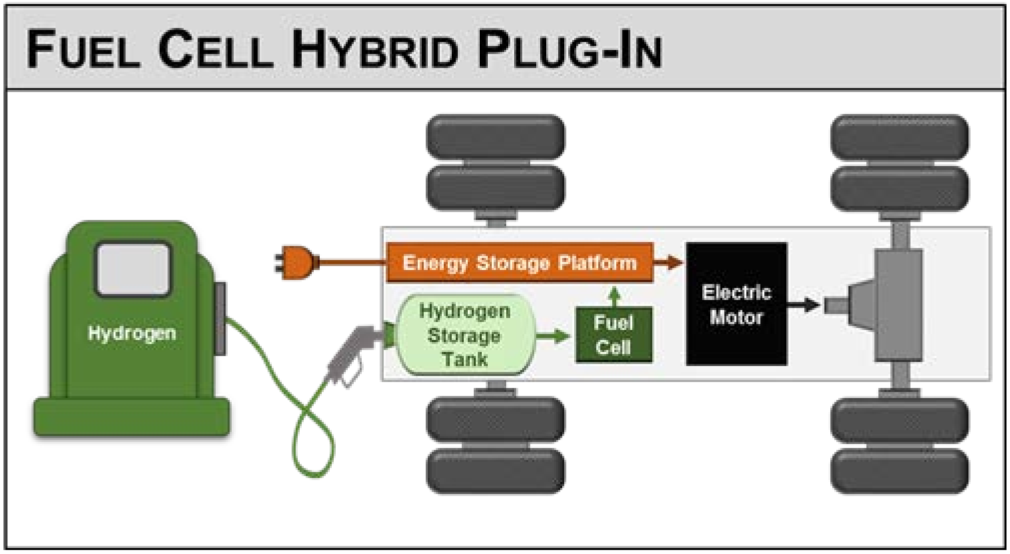

Figure 5- Overview of fuel cell plug-in hybrid bus powertrain

Refueling and Recharging Strategies and Facilities

Fuel cell plug-in hybrid bus requires recharging and refueling infrastructure, which in turn increases the requirements for space. It is common among all demonstrations that the bus is charged overnight while being plugged in to the electric grid. Fueling the onboard hydrogen has been guided by the access to an existing hydrogen fueling station. As fuel cell has complementary in propelling the bus, the required amount of hydrogen is less compared to fuel cell buses and thus, the hydrogen tanks are less in number.

Fueling time varies depended on the fill rate, with a "slow fill" to take between two and four hours to fill a 13-kg onboard hydrogen tank at 350 bar (180 miles, 290 km driving range). In contrast, a "fast fill" for this tank size can be completed at 414 bar on average in 15 minutes (Bubna, Brunner, Gangloff, Advani, & Prasad, 2010). In general, information on hydrogen refueling and battery charging for fuel cell hybrid plug-in bus implementations in the U.S. besides the hydrogen fuel supplier and hydrogen source is limited.

Specific infrastructure requirements for fuel cell hybrid plug-in buses, beyond those previously described for battery electric and fuel cell buses, have not been reported. Combining the location of battery-charging and hydrogen supply facilities into one increases space requirements.

Typical Route Assignments/Scheduling

Considerations similar to the previous two technologies (e.g., range, visibility, and location of fueling or charging stations) apply to this bus technology as well.

Performance measures

Fuel economy

Given the limited implementations of fuel cell hybrid plug-in buses, very little in-service performance information is available for specific transit agency implementations. This information is limited to fuel economy values. Similar results have been reported across the various fuel cell hybrid plug-in bus models: 7.1 (EVAmerica), 7.9 (Ebus), and 7.7 (Proterra average) mpdge. The best fuel economy (12.0 mpdge) was from the Ebus operated by the University of Delaware; however, this value was reported by the bus manufacturer and not measured based on real-world operations.

Availability and reliability

Transit agencies have consistently reported significant downtime for fuel cell hybrid plug-in buses related to a variety of issues with the batteries, fuel cell system, and hybrid integrator. Extended repair times have been attributed to challenges in diagnosing faults (Leslie Eudy, Post, Gikakis, Eudy, & Post, 2016).

Emission savings

Tank-to-wheel atmospheric pollutant emissions associated with fuel cell hybrid plug-in buses are zero. However, it is important to note that hydrogen production and distribution processes are responsible for emissions. The only comparison of emissions between fuel cell hybrid plug-in buses and traditional diesel buses found has been performed in Brazil. Fuel cell hybrid plug-in buses were associated with decreased emissions of CO2 (151.5 g/mile), particulate matter sized below 10 µm in diameter (159.8 g/mile), NOx (156.5 g/mile) and hydrocarbons (136 g/mile), when compared with engine exhaust released from conventional diesel buses (de Miranda et al., 2017).

Costs

Capital Cost

Limited information is currently available regarding bus costs, as fuel cell hybrid plug-in buses remained in an early prototype phase. Proterra reported that the fuel cell hybrid plug-in bus model developed for its round-robin demonstrations with BurbankBus, COMET, CapMetro, and Flint MTA cost $1.2 million. Proterra fuel cell hybrid plug-in buses were given on loan to each of these transit agencies for their respective demonstrations.

Infrastructure cost

Specific infrastructure requirements for fuel cell hybrid plug-in buses, beyond those previously described for battery electric and fuel cell buses, have not been discussed in the literature. Co-locating battery-charging and hydrogen supply facilities increases space requirements at these sites.

Operation Cost

Only one transit agency has reported the costs of hydrogen fuel and electricity to calculate the overall mileage costs for fuel cell hybrid plug-in bus operation. COMET noted operation of the Proterra fuel cell hybrid plug-in bus cost at $1.38 per mile in fuel expenditures (Leslie Eudy, Renewable, & Chandler, 2011). This cost is similar to that of other fuel cell bus technologies (see Table 5).

Maintenance cost

No information is available at this time regarding maintenance costs. A mechanic from the bus manufacturer has typically been staffed at the transit agency for the duration of the demonstration.

DISCUSSION

This section serves as an overall review and comparison of the implementation of zero-emission technologies, focusing on lessons learned and the challenges that are still present. Further, a comparison among the three technologies is presented, illustrating the strengths and weaknesses of them.

Comparison among technologies

The three technologies are compared in terms of monetary cost, efficiency, energy and emissions savings, and performance. Table 9 summarizes the ranges that have been reported for each metric used. All the information presented is based on the information available as of 2017 for the various technologies.

The initial cost of a battery electric bus is higher than that of a conventional diesel bus, but the life cycle cost has been estimated as lower (Seki, Hendrickson, & Stine, 2016). Typically, the cost to purchase a battery electric bus is about $300,000 more than that of diesel buses (Aber, 2016), but the bus manufacturers claim that these buses as a whole have a 40% longer lifetime (L Eudy, Chandler, & Gikakis, 2007), and annual savings are estimated at $39,000 per year over the 12-year lifetime of the bus (Aber, 2016).

The capital cost of battery electric buses is lower than that of the fuel cell-based buses, mostly due to the reduced battery costs over time (Lajunen & Lipman, 2016). In U.S., battery electric buses are being implemented on a larger scale and for a greater number of years than fuel cell buses. However, CARB has predicted that eventually the value of fuel cell battery electric buses will drop and stabilize, on the contrary of battery electric ones that are expected to cost more than today.

Overall, battery electric buses outperform diesel, CNG, and fuel cell-based buses in terms of efficiency, reporting a fuel economy five to six times higher than those of diesel and CNG buses and three to four times higher than that of fuel cell-based vehicles. Additionally, battery electric buses have lower fuel and maintenance costs compared to those of all other bus technologies. The battery electric bus technology also appears to be the most reliable, reaching high levels of miles between road calls and availability. The range of battery electric and fuel cell-based buses varies depending on the energy storage unit onboard, but it can be at levels comparable to those of diesel and CNG buses. With recent advances in battery technology, battery electric buses can reach a range of 350 miles, which is currently higher than any other zero emission bus technology.

A further cost analysis was performed for two agencies, Foothill Transit and AC Transit, in order to conclude in a total cost per bus value for battery electric and fuel cell buses. These two agencies were chosen as all needed information was available for both of them and specifically, collected from the same source: NREL. Further, they both deploy zero-emission fleets of same size and their service areas have similar characteristics.

Cost components that were taken into account include: bus capital cost and infrastructure cost, fuel cost and maintenance cost per mile. Considering a 12 years' bus lifetime and monthly average mileage per bus we estimated the total fuel and maintenance cost per bus for both zero-emission technologies. AC Transit has reported higher mileage for its fleets, however the values are comparable. Infrastructure cost per bus was also estimated and were added to the final value. For AC Transit it is known that the Emeryville fueling station costed about $10 million, however given that is a station that fuels light duty vehicles, this amount cannot be considered an investment for buses. As infrastructure cost for liquid delivery for a fleet size of 5 to 20 buses, we used Ballard's estimations. For Foothill Transit, the amount corresponds to the purchase and installation of two in-depot chargers. The numbers are presented in the following table (Table 8). In total, fuel cell bus cost is almost 4 times higher than the cost of a battery electric bus. Fleet size is a determinant of the per bus cost, however it is not clear what is the cost of expanding the infrastructure when the fleet increases. For fuel cell buses the hydrogen cost depends upon the hydrogen fueling method and the fleet size.

Table 8-Total cost per bus for battery electric and fuel cell buses

	BEB	**FCB**
Fleet size	12	13
Capital cost ($/bus)	900,000	2,500,000
Infrastructure cost ($/bus)	998,000	5,000,000
Infrastructure cost ($)	83,167	
Fuel cost ($/mile)	0.44	1.45
Fuel cost ($/bus)	145728	584640
Maintenance cost ($/mile)	0.21	1.25

Maintenance cost ($/bus)	69552	504000
Mileage (miles/month/bus)	2,300	2,800
Operation time (months)	12	
Lifetime (years)	12	
Total cost ($/bus)	1,198,447	3,588,640

In terms of emission and energy savings, all the technologies produce tank-to-wheel zero tailpipe emissions, and therefore, a well-to-wheel approach makes more sense in revealing the total benefits, since that accounts for the emissions associated with the production of the fuel used. However, even in this case, it is difficult to extract results from existing studies that can be compared against all the technologies, because different studies base their findings on different assumptions. For the emission and energy savings or measurements, available information was derived mostly from published literature, since only a few transit agencies have conducted relative studies. WRTA reported that as of 2017, it has reduced its emissions by 780 tons of CO_2 over the course of about four years, and Clemson Area Transit reported that it has eliminated 850 tons of CO_2 in less than three years (October 2014 to May 2017).

Lessons Learned

Across the transit agencies that implemented or demonstrated zero-emission transit buses, most were found to have had a positive experience from the implementation of zero-emission buses. There are four takeaways for the success of zero-emission bus implementations. First, the transit agency needs to start with a small fleet and eventually increase its size. This way they will be able to explore the technology and maintain a smooth operation of the transit fleet. Understanding the technology and properly choosing the one that matches the needs, conditions, and limitations of a transit agency and service area is also a key aspect. Then, maintenance procedures are crucial in order to properly operating a zero-emission fleet. Transit agencies have to invest time and money in training drivers and maintenance personnel while enabling information exchange between stakeholders for troubleshooting purposes. However, the training especially for maintenance purposes is more complicated, as it is expected to have a high initial cost, as the staff starts the learning process, which will eventually stabilize. Finally, having an effective level of collaboration, cooperation, and support (both monetary and non-monetary) between stakeholders substantially improves troubleshooting. The latter includes maintaining inventories for the equipment and also sharing gained knowledge.

Remaining consideration regarding battery electric buses deployment and operation are related to charging infrastructure and cost. The agency needs to decide on the charging method and then locating and installing the appropriate infrastructure in combination with scheduling and route assignment. Demand charged need to be take into consideration when deciding the type of charging method. It has been reported the need to establish an active partnership with electrical companies and on the same time, to ensure enough capital funding from the beginning of the project and incorporate monitoring systems to maintain batteries and reduce maintenance costs. For the case of fuel cell buses, a main step in their promotion was the introduction of U.S.-based market that targeted in the introduction of a bus configuration (American Fuel Cell Bus). This created a network among three suppliers and the respective transit agencies and allowed them to communicate, share information and maintain an inventory for the needed equipment. The initial demonstrations (approximately from 2003 to 2010) suffered a lot from extended bus downtimes (Leslie Eudy & Post, 2014), as it was not easy to replace supporting equipment and fuel cell components that had to be shipped outside of the country. For AC Transit specifically this is still an issue as the bus manufacturer it is outside of the U.S. (Leslie Eudy & Post, 2017).

The main challenge for U.S. fuel cell-based fleets is the small-scale deployment. All of the agencies operate small number of buses, which cannot justify the allocation of resources for training and infrastructure purposes. Operation and maintenance costs are higher. Additionally, small fleets do not allow operators to explore and understand the technology; it has been reported that they have trouble recalling the required actions to deal with a certain problem as it occurred to another bus a long time after it did to the first one. One approach to this problem is recording and sharing the troubleshooting procedures among different practitioners.

Fuel cell plug-in hybrid buses were mostly demonstrated for a short period of time. By operating the same bus to different locations, Proterra and Ebus gained some information on its performance, but it is not enough to draw solid conclusions on it.

Table 9- Summary of typical bus characteristics across all zero-emission bus technologies

	Battery Electric Bus	Fuel Cell Bus	Fuel Cell Hybrid Plug-In Bus	Diesel	GNG
Capital Cost ($)	Depot charging: 733,000–919,000 On-route charging: 800,000–1,200,000	FTA target: 1.0 million Active fleets: 1.8–2.5 million	Loan from Proterra: 1.2 million	445,000	400,000–495,000
Fuel economy (mpdge or mpg)	8–29.0	6.06–7.83	7.1–7.9	3.8–5.4	2.79–3.33
Fuel cost per mile ($/mile)	0.18–0.72	1.30–1.58	1.38	0.18–0.90	0.29–0.61
Electricity cost ($/kW)	0.17	NA	0.05	NA	NA
Hydrogen cost ($/kg)	NA	4.52–23.46	9.93	NA	NA
Maintenance cost per mile[a] ($/mile)	0.16–1	0.39–1.31	0.55	0.25–3	0.22–0.61
Max. speed (mph)	NR	37–55	44.7–58	45–50	NR
Max acceleration (m/s^2)	NR	NR	0.73	NR	NR
Availability (%)	84–98	45–88	35–58	>85	78–94
Miles between road calls (MBRC)	6,000–9,000	3,830–6,335	NR	3,400	10,511[1]
Average monthly miles (miles)	2,500	~2,500	491–547	4,500	3,900
Range (miles)	50–350 Fast Charge: 49–62 Slow Charge: 136–193	210–325	Only-battery: 30–40 Fuel Cell & Battery: 280–300(Leslie Eudy, Post, & Gikakis, 2015)	280–690	217
Charging/ fueling time	Fast charge: 6–15 min Slow charge: 4–6 hrs	6–24 mi	Fast fill: 15 min Slow Fill: 2–4 hrs	NR	NR
Energy savings	NR	up to 36%	2.58 (kWh/mi)	NA	NA
Fuel cycle GHG emissions (g CO_2-eq/mile)	12-428	77-264	NR	535	535
Well-to-tank CO_2 emissions (g CO_2/MJ)	77	117	NR	19	25.9

	Battery Electric Bus	Fuel Cell Bus	Fuel Cell Hybrid Plug-In Bus	Diesel	CNG
Noise (dB(A))	Interior-Standing: 44.7-52.6 Accelerating: 68.3-67.1 Exterior: Constant Acceleration: 57.8-67.1 Standstill Acc.:55.9-66.1 Stationary: 36.1-54.2	Interior Standing: 62 Accelerating (0-30 mph): 65 Accelerating (0-55 mph): 71	NR	Interior-Standing:46.1-61 Accelerating: 68.9-80.1 Exterior: Constant Acceleration: 73.2-79.8 Standstill Acc.: 69.7-79.4 Stationary: 57.4-77.7	Interior -Standing: 44.4-59 Accelerating: 69.7-77.9 Exterior: Constant Acceleration: 69.2-75.5 Standstill Acc.: 74.6-76.4 Stationary: 65.7-76.9
Technology Readiness Level (TRL)	7 (2017)	7-8 (2017)	6 (2016)	9	9

NR: Not reported; NA: Not applicable

- *Maintenance costs and miles between road calls could vary depending on the bus age.*
- *The battery electric, fuel cell, and fuel cell hybrid plug-in considered for this table are either 35 or 40 feet long.*
- *Estimates vary based on the type of power plant fuel (for battery electric buses) or fuel for hydrogen production (for fuel cell buses); estimates made using LEM from UC Davis.*
- *Assumptions include: Diesel and CNG: GREET model; Hydrogen: CA-GREET 2.0 assuming 100% steam reforming of natural gas from North America; Electricity: 2010 EPA Electricity emission factors.*
- *Noise studies measure noise level as one would experience it inside the bus (interior) and outside of the bus (exterior).*
- *For active implementations.*

CONCLUSIONS

This study presents a comprehensive review of zero-emission transit bus implementations by transit agencies across the U.S. Transit agencies have used three technologies to reduce their transportation-related GHGs: battery electric, fuel cell, and fuel cell plug-in hybrid electric buses. One objective is to map in detail all the stages and considerations one transit agency needs to have in mind in case of showing interest in zero-emission buses. Even if the focus area is U.S., revealing the experience of transit agency representatives can provide insights to other countries worldwide.

For U.S., it seems that battery electric buses are the main technology considered from the agencies, as it is already widely developed across the country. As the main limitation of this technology is the driving range, it is interesting to see how the new Proterra bus will operate, as it has an increased range. Then, next steps for battery electric buses is the optimization of routing and scheduling with respect to charging infrastructure. Finally, in order to achieve well-to-wheel emission-free transportation it is expected from the agencies to produce electricity from alternatives sources.

Fuel cell battery electric buses are also a considerable zero-emission option, even though it less developed in the U.S. Implementations have shown improvement of performance measures across time and the technology is approaching the goals that have been set by the U.S. DOT.

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