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Battery-electric transit bus developments and operations: A review

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ABSTRACT

In this article, we review the worldwide developments of battery-electric buses (a) from medium-sized vehicles (e.g., 6.7 m) to heavy-duty vehicles (e.g., 11 m), and (b) from the slow-charging mode (e.g., 6 hours) to the fast-charging mode (e.g., 10 minutes). We also review the worldwide operations of battery-electric buses (a) from 1907 in London, England, the early 1980s in Denver, Colorado, and the early 1990s in Santa Barbara, California, and Chattanooga, Tennessee, to various international cities now, and (b) from less than 20 vehicles in a transit agency to more than 1,000 vehicles. We summarize the experiences and lessons learned from real-world operations. We examine key technical specifications that are critical to the operations of electric bus systems, in particular the operational distance and charging time. Due to a limited operational range of battery-electric buses, three range remedy methods have been proposed: (a) regular (slow) battery charging with backup vehicles equipped with fully charged batteries; (2) battery swapping; and (3) fast opportunity charging during the layover period. We conduct a qualitative analysis on the strengths and weaknesses of each range remedy method. We also analyze the vehicle cost, energy cost, and emissions of transit buses powered by different sources, and examine potential impacts of fast-charging electric buses on the electric grid.

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1. Introduction

Public bus service plays an important role in the daily life of many people living in urban and suburban areas. Bus transportation is especially beneficial for people who do not own a personal car. Diesel-powered buses were once dominant in bus transportation; about 92% of buses were powered by diesel before 2000 in the United States (National Transit Database, 2013). However, as heavy-duty vehicles, diesel-powered buses also emit a large amount of air pollutants and global greenhouse gases. It is estimated that more than 45% of nitrogen oxides and 75% of particulate matter are generated by heavy-duty diesel trucks and buses (Elkins et al., 2003). Aiming to reduce local air pollution caused by diesel buses, public transportation agencies are transitioning to buses powered by alternative energy sources, such as compressed natural gas, liquid natural gas, etc. According to the National Transit Database, the percentage of diesel buses used in U.S. transit agencies has decreased from 98.8% in 1992 to 69.0% in 2011 (see Figure 1). In particular, battery-electric buses have been used in many transit agencies. A unique advantage of battery-electric buses is zero vehicle emissions generated in service areas. Similar to trolley buses, battery-electric buses can also take advantage of regenerative braking to recover energy during the braking process. However, battery-electric buses generally have a much shorter operational range than buses powered by other energy sources. In this article, we will review the developments and operations of battery-electric buses.

Transportation electrification has received significant attention recently (Parag, 2010). However, the use of battery-electric buses is not a new development. As early as 1907, battery-electric buses were introduced in London to replace the horse (*The Economist*, 2007). Denver, Colorado, introduced six battery-electric buses in 1982 (NCR Technology, 1982), and Santa Barbara, California, and Chattanooga, Tennessee, introduced a number of electric buses in the early 1990s (Dugan, 1994; Griffith & Gleason, 1996). The majority of battery-electric buses used by transit agencies prior to the mid-2000s were approximately 6.7 m long. Since then, due to advances in bus manufacturing and battery techniques, manufacturers have developed heavy-duty electric buses approximately 12 m long with a much longer range or with fast-charging capabilities. Recently, battery-electric buses have received significant attention from the world. In 2012, Uruguay signed a deal for 500 heavy-duty electric buses (Richard, 2012) and Tel Aviv, Israel, ordered 700 electric buses (Shamah, 2012). Shenzhen, China, ordered 1,000 heavy-duty electric buses in 2013 (She, 2013). *Scientific American* also reports the use of battery-electric buses by LINK Transit in Wenatchee, Washington, and Foothill Transit in Los Angeles, California (Chambers, 2012). The large-scale use of electric buses may be motivated by government incentives, such as the TIGER program in the United States, the Green Bus Fund Program in the UK, and the Ten Cities and Thousand Vehicles Program in China. The German government also initiated a program, Electric Mobility, to motivate research and development of transportation electrification, including electric buses and hybrid buses (Germany Federal Ministry of Transport, Building and Urban Development, 2011).

A number of studies have investigated battery-electric bus systems. EPRI (1998) reported on battery-electric bus projects in the United States, including project history, lessons learned, and technical specifications of electric buses.

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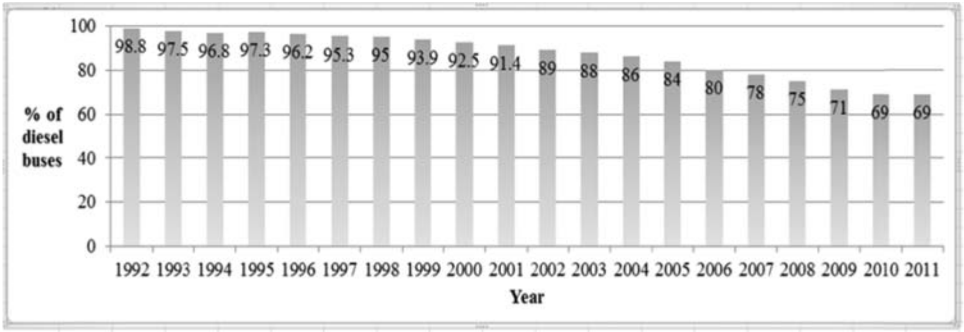

Figure 1. Percentage of diesel buses (raw data: National Transit Database, 2013).

Callaghan & Lynch (2005) reviewed the technologies and applications of battery-electric, fuel-cell, and hybrid-electric buses. Eudy & Gifford (2003) examined the challenges and experiences of various types of electric buses, focusing on analyzing energy storage mechanisms and electric propulsion systems. All these reports are based on operations before the mid-2000s in the United States. Fowler and Euritt (1995) conducted a feasibility analysis of electric buses in Austin, Texas. Tzeng, Lin, and Opricovic (2005) conducted a multi-criteria analysis for transit buses powered by alternative fuels. Haggis and Beback (2010) listed certain technical specifications from some battery-electric bus manufacturers. Wang and Gónzalez (2013) conducted a feasibility study of electric buses in small and medium communities.

The objectives of this article are to (a) review battery-electric bus developments on an international scale from the early 1980s to the present day; (b) examine and present the key specifications of battery-electric buses that are relevant to operations of electric bus systems; (c) summarize the experiences and lessons learned from real-world operations; (d) classify methods to overcome the short operational ranges for battery electric buses; and (e) conduct a qualitative analysis on the strengths and weaknesses of each range remedy method.

2. Battery-electric bus developments and specifications

In this section, we first describe the developments and operations of battery-electric buses. We then examine and present the key specifications of certain battery-electric buses in the market. We will focus on battery-electric buses for transit service. Fuel-cell buses, ultra-capacitor buses, diesel-hybrid buses, or battery-electric school buses are not discussed.

2.1 *A description of developments and operations*

We roughly divide developments and operations into two periods: before and after the mid-2000s. Before the mid-2000s, the majority of battery-electric buses in service were 6.7 m buses with regular charging (in approximately 6 hours). Since the mid-2000s, heavy-duty electric buses have been the focus of development and operations, and fast-charging capability has also been developed.

2.1.1 *Before the mid-2000s*

To the best of our knowledge, the earliest introduction of battery-electric buses occurred in London in 1907. The electric bus was powered by lead-acid batteries weighing 1.5 tons. It was able to carry 34 passengers and travel 60 km on a single charge. Battery swapping was used during lunchtime in order to extend the service range. However, this development was discontinued due to a patent fraud (*The Economist*, 2007).

In the United States, the Regional Transit District (RTD) in Denver, Colorado, purchased six battery-electric buses manufactured by BMI in order to mitigate air pollution near a major mall in downtown Denver (Tables 5−9 in EPRI, 1998; NCR Technology, 1982). These electric buses were 12.2 m long, which was very long even relative to the current standard. They were powered by lead-acid batteries. The operational range was rather short: about 37 km with 73% depth of discharge (NCR Technology, 1982). During the night, these buses were parked at a garage that was 5 km from the starting bus stop (NCR Technology, 1982). It is worth mentioning that some attempts were made to extend the operational range in 1982, such as using battery swapping and partial charging (NCR Technology, 1982).

The Metropolitan Transit District (MTD) of Santa Barbara, California, introduced two battery-electric buses in 1991. Interestingly, the primary stimulus for this was increasing ridership rather than reducing emissions (Griffith & Gleason, 1996). Two buses were manufactured by BMI (see Tables 5−17 in EPRI, 1998). Since then, ridership had steadily increased. MTD then purchased six additional electric buses manufactured by Specialty Vehicle Manufacturing (SVM). All these buses were 6.7 m long and powered by lead-acid batteries (see Tables 5−17 in EPRI, 1998). An operational report by MTD shows a five-fold increase in ridership during the first year of all-electric operations (Griffith & Gleason, 1996). The average operational range is about 130 km, which is generally long enough for a whole day service in the MTD service area. Charging takes 8 to 10 hours; no battery swapping or opportunity charging was performed (Griffith & Gleason, 1996). Note that electric buses in MTD are open-air buses, therefore, no air-conditioning is needed, which can save energy. As of July 2005, MTD operated 20 battery-electric buses (Callaghan & Lynch, 2005), which comprises the largest fleet in the United States.

In order to mitigate severe air pollution, Chattanooga Area Regional Transportation Authority (CARTA) of Chattanooga, Tennessee, introduced battery-electric buses on a downtown shuttle loop (Dugan, 1994). In 1992, CARTA purchased two electric buses manufactured by SVM (Argonne National Laboratory, 1997). Together with the partners, CARTA then reached a conclusion to build battery-electric buses for use in Chattanooga and to export them to other cities (Dugan, 1994), which led to the creation of Advanced Vehicle Systems (AVS). CARTA then ordered 12 battery-electric buses manufactured by AVS in the fall of 1992 (Argonne National Laboratory, 1997). All these buses were 6.7 m long and powered by lead-acid batteries (see Tables 5−8 in EPRI, 1998). CARTA utilized battery swapping to effectively extend the short range of their electric buses. Because there were about two to three battery sets in a bus, swapping was often done manually, which took 10 to 15 minutes. The batteries swapped out were then fully charged in 6 to 8 hours (Argonne National Laboratory, 1997). As of July 2005, CARTA has operated 12 battery-electric buses (Callaghan & Lynch, 2005).

With the success of Chattanooga and Santa Barbara, many cities introduced a few battery-electric buses. Based on case studies in EPRI (1998), Table 1 lists the use of battery-electric buses in the United States before 1998, including the city, fleet size, operational range, motor type, battery type, vehicle size, and bus manufacturers.

Electric buses have also received attention in Mexico. In 1993, the National Autonomous University of Mexico (NAUM) designed and built a prototype of an electric bus with 13 seats, powered by lead-acid batteries (Romero, Chicurel, & Soto, 1993). The NAUM collaborated with Mexico City in 1998 in an attempt to build an electric bus route (Serrania, Chicurel, López, & Sheinbaum, 2000).

In 2004, Yanzhou, Shandong Province, China, introduced 12 small-sized electric buses, manufactured by Aucma. These buses have eight seats and are powered by lead-acid batteries. The operational range is about 80 km, and the charging time is 6 to 7 hours (Zhang, 2004).

Battery-electric bus transportation before the mid-2000s has the following features:

1. The fleet size is rather small. Even the leading agencies, Santa Barbara and Chattanooga, have no more than 20 electric buses (see Table 1).
2. The majority of vehicles are 6.7 m buses. As of 1998, there were only about 20 electric buses longer than 9.1 meters (see Table 1). As of 2005, most electric buses are 6.7 m long (Callaghan & Lynch, 2005).
3. Lead-acid batteries are the primary battery type, and there are a number of buses powered by Nickel-Cadmium (NiCad) batteries, as shown in Table 1.
4. There is no major difference between the use of AC or DC motors (see Table 1).
5. The major motivation for introducing battery-electric buses is to reduce air pollution (see Project History of various agencies in Chapter 5 of EPRI, 1998).

Table 1 shows that there were seven major bus manufacturers as of 1998 in the United States. Due to the limited market, a major bus manufacturer, AVS, has gone out of business.

Table 1. The use of battery-electric buses in the United States as of 1998 (raw data from case studies in EPRI, 1998).

		Range (km)		Motor		Battery		Vehicle size (feet)									Bus manufacturer						
City	Buses	Avg	Max	AC	DC	Lead-Acid	NiCad	19	22	25	26	31	32	33	35	40	APS	AVS	Blue Bird	BMI	Electricar	EVI	SVM
Santa Barbara, CA	18	120	160	8	10	10	8		11		5				1		9			3			6
Chattanooga, TN	16	69	154	9	7	15	1		13			3						11					5
Berkeley, CA	7	56	72		7	7			7												7		
Miami Beach, FL	7	61	72	7		7			7									7					
Denver, CO	6	48	48		6	6										6				6			
Cedar Rapids, IA	4	112	128	4		4								4					4				
Charlotte, NC	4	80	112		4	4			4									4					
Savannah, GA	4	80	96		4	4			4									4					
Atlanta, GA	3	64	72	3		3												2	1				
Birmingham, AL	3	80	96	3		3			3									3					
Charlottesville, VA	3	64	77		3	3			3									3					
Framingham, MA	3	—	—		3	—	—		3														3
Grand Canyon, AZ	3	154	224	3			3			3							3						
Los Angeles, CA	3	80	112		3	3			3														3
Portland, ME	3	64	64	3		3			3									3					
Richmond, VA	3	80	96	3		3							3						3				
Sacramento, CA	3	—	—	—	—	—	—		3												2		1
Santa Monica, CA	3	144	176	3			3				3						3						
South Bend, IN	3	—	—	3		3			3									3					
Anderson, IN	2	96	160		2	2			2				1					2					
East Boston, MA	2	—	—	—	—	—	—		2									2					
El Monte, CA	2	—	—	—	—	—	—																2
Fresno, CA	2	112	112		2	2		1	1													2	
Nashville, TN	2	72	96	2		2			2									2					
Yosemite Park, CA	2	112	128	2		1	1					2					1						1
Allentown, PA	1	—	—	—	—	—	—		1									1					
Burlington, VT	1	—	—	—	—	—	—		1									1					
Palm Desert, CA	1	—	—	—	—	—	—		1														1
Pinellas Park, FL	1	—	—	—	—	—	—		1									1					
San Francisco, CA	1	—	—	—	—	—	—		1												1		
Torrance, CA	1	—	—	—	—	—	—					1											1
Total	117							1	79	3	8	6	4	4	1	6	16	49	8	9	10	2	23

Note. — = data unavailable.

As of July 2005, the largest electric bus company is Ebus (Callaghan & Lynch, 2005).

2.1.2 After the mid-2000s

Since the beginning of the 21st century, mitigating air pollution has become an increasingly important motivating factor in the development and operation of battery-electric buses. Around the mid-2000s, battery and bus manufacturing techniques advanced greatly. First, a fast-charging technique was developed by a few companies, and charging can now be done in 10 to 30 minutes. Second, electric bus manufacturers emphasize the development of heavy-duty buses with a much longer operational range. Note that although six 12.2 m electric buses had been used in Denver since 1982, the operational range was only about 48 km (see Table 1).

2.1.3 North America

In 2010, Foothill Transit in the metropolitan Los Angeles area introduced three 10.7 m battery-electric buses with 37 seats to serve Route 291, which travels between the cities of La Verne and Pomona, east of Los Angeles (Foothill Agency, 2010). These buses, EcoRide, are manufactured by Proterra and powered by lithium batteries. The operational range is about 48 km (Quick, 2010). Although the operational range and vehicle size are similar to those proposed in the early 1980s in Denver, these electric buses by Proterra can be charged in 10 minutes using Proterra's inductive fast-charging stations. In comparison, charging time was generally 6 to 8 hours for the buses developed before (EPRI, 1998). Fast opportunity charging is done during the layover time of bus drivers at a station in Pomona. The lithium batteries are produced by Altairnano in Nevada; and the fast-charging station components are built by Aerovironment in California (Federal Transit Administration, 2012). Since 2010, EcoRide buses have been introduced in a number of cities in the United States (Proterra, 2013b).

Ebus is an important manufacturer that produces 6.7m battery-electric buses with charging time of a few hours (Callaghan & Lynch, 2005). Ebus develops 6.7m buses powered by lithium batteries, which are manufactured by Nevada-based Altairnano (Federal Transit Administration, 2011). Charging is expected to be done in 5 to 10 minutes. In 2011, LINK Transit in Wenatchee, Washington, ordered five buses, two fast-charging stations, and one slow-charging station from Ebus (Pratt, 2012). Once these electric buses arrive, they are planned to be in operation on Routes 9 and 19, which are about 8 km (Pratt, 2011a) in length.

Battery-electric buses have also been used in Canada. Three compact electric buses, 5.3 m Gulliver U520ESP produced by Tecnobus, have been in operation in Quebec since 2005 (Transport Canada, 2012). A 12.2 m electric bus powered by lithium-ion batteries has been developed by Mitsubishi Heavy Industries and New Flyer; it is currently under operational testing in Manitoba, Canada (Mitsubishi, 2012). Nova Bus together with Bathium Canada, TM4, Giro, Rene Materiaux Composites, and Precicad is designing and manufacturing a 12.2 m electric bus; the project is sponsored by Quebec, Canada (Nova Bus, 2012).

2.1.4 Asia-Pacific

In 2009, the Seoul Metropolitan Government signed an agreement with Hankuk Fiber and Hyundai Heavy Industries (HHI) to develop battery-electric buses with fast-charging capabilities (Seoul Metropolitan Government, 2012). In December 2010, five battery-electric buses were introduced in Seoul to serve on the Mt. Namsan circular route in Seoul (Kim, 2011). These buses are 11 m long and have 23 seats; their operational range is between 83 km and 110 km; and they are powered by lithium-ion batteries with charging time from 20 to 30 minutes (Kim, 2011; Seoul Metropolitan Government, 2012). Another company in Korea, Hyundai Motor, unveiled a battery-electric bus in 2010; the developed model, Elec-City, has a range of 120 km and can carry 51 people (Hyundai, 2010).

Beijing adopted 50 battery-electric buses with battery swapping during the Beijing Olympics in 2008 (Beijing Municipal Commission of Transport, 2012). In fact, 14 battery-electric buses were in pilot testing as early as 2005 (Cui, 2008). Powered by lithium manganese batteries, these electric buses have 50 seats and a 130 km operational range; they were initially designed by The Beijing Institute of Technology and were manufactured by Jinghua Coach (EV World, 2008), which subsequently went out of business. Foton Company now manufactures battery-electric buses for Beijing. Currently, about 100 battery-electric buses are in operation on Routes 81 and 84 (Beijing Municipal Commission of Transport, 2012). Battery swapping is conducted automatically.

Battery-electric buses were introduced during the Shanghai World Expo (United Nations Environment Programme, 2009) in 2010. In total, 120 battery-electric buses, 12 m long, were used in service: 60 buses followed the technology used in the Beijing Olympics, and the other 60 buses were manufactured by Sunwin (Cai, 2012a). The operational distance is 150 km when an air conditioner is on; battery swapping can be finished in 10 minutes (United Nations Environment Programme, 2009). During a 184-day period, these buses were operating for more than 4,000,000 km on three routes (Cai, 2012b).

In order to mitigate air pollution, the Chinese government initiated the Ten Cities and Thousand Vehicles Program in 2009 to stimulate electric vehicle development through large-scale pilot tests (Ministry of Finance, China, 2009). Local agencies can get reimbursements on 500,000 RMB from the central government for each battery-electric bus purchase. Such an incentive motivates almost all major bus manufacturers in China to develop battery-electric buses. We will focus on the operations in Shenzhen and Chongqing: the former city is currently operating the largest number of electric buses, and the latter city is using the fast-charging strategy.

As one of the richest cities in China, Shenzhen has made the strongest effort to promote the use of battery-electric buses. Shenzhen operates 253 electric buses as of 2012: 200 buses from BYD and 53 buses from Wuzhoulong (Sun, 2012). Shenzhen ordered 1,000 heavy-duty electric buses and plans to deploy them for transit service in 2013; among these 1,000 vehicles, 540 buses are from BYD, 360 buses are from Wuzhoulong, and 100 buses will be purchased from BYD or Wuzhoulong, whichever shows better performance (She, 2013). Regular charging is used in Shenzhen, which often takes about 2 hours (Sun, 2012).

Among electric bus manufacturers in China, Hengtong is currently the only one that has developed the fast-charging technique (Hengtong, 2013). Hengtong produces 12 m electric buses with an operational range of 40 to 50 km; the buses are powered by lithium titanate batteries; and charging can be completed in 10 minutes, according to Hengtong (2013). The batteries are supplied by Microvast (Song, 2012), a company with offices in Texas. As of September 2012, 25 battery-electric buses with fast-charging capabilities have been in operation in Chongqing (51lDC, 2012).

Battery-electric buses have also received attention in Taiwan. Two battery-electric buses have been in operation since October, 2012, in Taipei (Lin, 2012); it is unclear which manufacturer produced these buses. The Environment Protection Agency of Taiwan plans to replace all 6,750 diesel buses by electric buses in 10 years (EPA Taiwan, 2012). Meanwhile, RAC, a manufacturer in Taipai, produces the 12 m bus RACE150; RACE150 is powered by yttrium lithium batteries (YLF) and can run 350 km before requiring a recharge, according to a company announcement (RAC, 2013). Charging can be finished in either 2 hours with the fast-charging mode or 7 hours with the regular charging mode.

Battery-electric buses have also been introduced in other Asia-Pacific countries. A battery-electric bus, the Tindo, has been in operation in Adelaide, Australia, since 2007; the batteries are charged using solar power (Adelaide City Council, 2007). In Sir Bani Yas Island of United Arab Emirates, two battery-electric buses have been in daily operation since 2011 (Liberty Automobiles, 2011). All these buses were manufactured by DesignLine (DesignLine, 2010), headquartered in North Carolina. According to DesignLine (2010), the operational range of the battery-electric bus, Eco-Smart 1, is 193 km. No information was available concerning power source or charging time.

2.1.5 *Europe*

In 2009, the UK launched the Green Bus Fund program to support the development and operation of buses with alternative energy in England (UK Department of Transport, 2009). Optare is a major battery-electric bus manufacturer in the UK. In 2009, Optare introduced Solo EV, a battery-electric bus 9.0 to 9.7 m long with 28 to 37 seats (EV World, 2009; Optare, 2012a). Solo EV is powered by lithium iron magnesium phosphate batteries (LiFeMgPO4) that is produced by Valance (Optare, 2012a). Solo EV can be fully charged by being plugged into a standard three-phase outlet in less than 8 hours (EV World, 2009). Solo EV has been used in Nottingham (eight vehicles), Durham (three vehicles), and Poundbury (two vehicles) (UK Department of Transport, 2013). Optare has developed another electric bus, the Versa EV. Versa EV is 11 m long and has 34 seats; powered by LiFeMgPO4 batteries, Versa EV can achieve between 120 and 153 km after a full charge in less than 2 hours (Optare, 2012b). Since 2012, three Versa EV buses have been in operation by Travel de Courcey in Coventry on a circular route between City Centre and War Memorial Park (Griffin, 2012). The charging time of Versa EV buses in Coventry is less than 40 minutes (Griffin, 2012). Note that the total round-trip distance between City Centre and War Memorial Park is about 6.4 km (estimated using Google Map with the route geometry published in Travel de Courcey, 2013). Therefore, partial charging can generate sufficient energy for the operation (M. Hayes, personal communication, February 22, 2013).

In France, an electric bus, Oreos 4X, has been in operation in Coulommiers since 2010 (Transdev, 2011). Oreos 4X is manufactured by PVI, a company located in Gretz-Armanvilliers, France. Oreos 4X is 9.3 m long and has 25 seats; its operational range is about 140 km; and it is powered by lithium-ion batteries and can be fully charged in 6 to 8 hours (PVI, 2011).

In Russia, Liotech, with partners, produced an 11.60 m battery-electric bus, the TROLZA-52501, in 2012 (Liotech, 2012b) powered by lithium-ion batteries. Its operational range is 120 km, and it can be fully charged in 3 hours according to Liotech (2013). TROLZA-52501 is expected to be in pilot operation in Moscow (Liotech, 2012a).

A German company, Conductix-Wampfler GmbH, developed a novel charging technique, inductive power transfer, where charging can be conducted when passengers board and alight the bus (Wechlin & Kusch, 2012). Together with partners, Conductix-Wampfler GmbH provided 7.5 m electric buses with 15 seats to two Italian cities: Turin with 23 buses (Wampfler, 2013b) since 2003 and San Martino with eight buses since 2002 (Wampfler, 2013a). Since 2012, Conductix-Wampfler GmbH with partners provided a 12 m bus for testing in the Netherlands (Wechlin & Kusch, 2012). It is worth mentioning that the inductive charging technique was also tested as early as the 1980s with the collaboration of the University of California—Berkeley and Santa Barbara Metropolitan Transit District (Shladover, 2007).

OTOKAR, a Turkish company, produced an electric bus, Doruk Electra, in 2012, which is 9 m long with 25 seats (Otokar, 2012). It is powered by lithium-iron magnesium phosphate batteries (Busworld, 2012) with an operational range of 280 km, and it can be fully charged in 6 to 8 hours (Otokar, 2012).

A Polish company, Solaris Bus, has developed battery-electric buses with optional lengths of 8, 9, and 12 m (Solaris Bus, 2013). Urbino-12, a 12 m long electric bus, has been in operation during the Euro 2012 football championship (Solaris Bus, 2012). Urbino-12 is powered by lithium-ion batteries with the operational range of 150 km and charging time of one-and-a-half hours (Solaris Bus, 2012).

An Israeli transit agency, the Dan Bus Company, ordered 700 electric buses from BYD in 2012 for service in Tel Aviv (Shamah, 2012).

2.1.6 *South America*

Uruguay had plans to operate 500 battery-electric buses manufactured by BYD by 2015 (Richard, 2012). Sao Paulo, Brazil plans to buy five electric buses from BYD (Ruters, 2012).

2.1.7 *Summary*

We briefly described the international development and operation of battery-electric buses. Our objective was to provide a general overview of electric bus development rather than to produce an encyclopedia. Table 2 lists the latest operations of electric buses in certain cities. Note that many cities in China are operating more than ten battery-electric buses. We then present only certain cities in China that operate a large number of battery-electric buses.

Recent battery-electric bus models have the following features: (a) the fleet size is becoming much larger because several cities are operating or plan to operate a few hundred electric buses; (b) lithium-ion batteries are the most widely adopted, while lead-acid

Table 2. Latest operations of heavy-duty battery-electric buses in certain cities.

Country region	City	Description	Major range remedy method
Australia	Adelaide	As of 2007, 1 bus from DesignLine (Adelaide City Council, 2007)	regular charging
Brazil	Sao Paulo	Plan to buy 5 buses from BYD (Ruters, 2012).	regular charging
Canada	Windsor	As of May 2012, 10 buses from BYD (EV World, 2012b)	regular charging
China	Beijing	As of Sep 2012, about 100 buses; in 2010, ordered 100 additional buses from Fotin and not in service yet; in Nov 2011, made the plan to use 1,000 additional buses by 2015 (Beijing Municipal Commission of Transport, 2012).	battery swapping with partial charging
	Changsha	As of Nov 2011, ordered 100 buses from BYD; made the plan to operate 1,000 buses by 2014 (Wang, 2011).	regular charging
	Chongqing	As of Sep 2012, 25 buses from Hentong (51IDC, 2012); made the plan to have 500 more buses in 2013 and bus manufacturer information unclear (Li, 2012).	fast charging and/or others
	Hefei	As of Jan 2013, more than 600 buses and the majority from Ankai (*Hefei Evening Paper,* 2013).	regular charging
	Qingdao	As of Aug 2012, about 200 buses from Sunwin and 5 buses from Yixing; made the plan to operate 1,000 buses by June, 2014 (Zhou, 2012).	battery swapping
	Shanghai	As of 2010, 100 buses; 50 buses from Sunwin (Cai, 2012a).	battery swapping
	Shenzhen	As of 2012, 200 buses from BYD and 53 buses from Wuzhoulong (Sun, 2012); made the plan to use 1,000 additional buses in 2013 from BYD and Wuzhoulong (She, 2013).	regular charging
	Tianjin	As of Feb 2013, 40 buses (Tianjin Administration Office of Passenger Trafficc, 2013).	battery swapping
France	Coulommiers	As of 2010, one bus from PVI (Transdev, 2011).	regular charging
Israel	Tel Aviv	As of Sep 2012, ordered 700 buses from BYD (Shamah, 2012)	regular charging
Italy	Turin	As of 2012, 23 buses from Wampfler and partners (Wampfler, 2013b).	fast charging
	San Martino	As of 2012, 8 buses from Wampfler and partners (Wampfler, 2013a).	fast charging
Netherlands	Schiermonnikoog	As of June 2012, 10 buses from BYD (EV World, 2012a)	regular charging
	s'Hertogenbosch	As of 2012, 1 bus in operation from Wampfler and partners (Wechlin & Kusch, 2012).	fast charging
Korea	Seoul	As of Aug 2011, 9 buses from Hankuk Fiber and Hyundai Heavy Industries (Kim, 2011)	fast charging
Taiwan	Taiwan	As of 2012, at least 2 buses in operations in Taipei; made the plan in 2012 to replace all diesel buses (about 6,750 vehicles) by electric buses in 10 years (EPA Taiwan, 2012)	Not available
UK	Coventry	As of Feb 2013, 3 Optare Versa EV (UK Department of Transport, 2013)	fast charging
	Nottingham	As of Feb 2013, 8 Optare Solo EV (UK Department of Transport, 2013)	regular charging
	Durham	As of Feb 2013, 3 Optare Solo EV (UK Department of Transport, 2013)	regular charging
	Poundbury	As of Feb 2013, 2 Optare Solo EV (UK Department of Transport, 2013)	regular charging
UAE	Sir Bani Yas Island	As of 2011, 2 buses from DesignLine (Info, 2011)	regular charging
Uruguay	Buquebus	Made the plan to buy 500 buses from BYD in 2015 (Richard, 2012).	regular charging
USA	Pomona, CA	As of 2010, 3 buses from Proterra (Foothill Agency, 2010).	fast charging
	San Antonio, TX	As of Feb 2013, 3 buses from Proterra (Davila, 2013).	fast charging
	Seneca, SC	Signed the contract in 2012 to buy 4 buses from Proterra (Mass Transit, 2012)	fast charging
	Stockton, CA	2 buses from Proterra in early 2013 (Ibarra, 2012).	fast charging
	Tallahassee, FL	Signed the contract in 2011 to buy 3 buses from Proterra (Green Energy News, 2011)	fast charging
	Wenatchee, WA	Plan to operate 5 buses from Ebus as early as 2013 (Pratt, 2011a).	fast charging

batteries are scarcely used anymore; (c) heavy-duty buses are becoming the development mainstream; and (d) the fast-charging technique has received considerable attention.

2.2 *Key technical specifications*

In this section, we present the key specifications of electric buses, including the operational range, vehicle size, battery type, battery capacity, charging time, charging power, estimated vehicle price, etc. These specifications are very important to the operations of battery-electric bus systems. Some manufacturers have not yet published technical specifications and such manufacturers' models are omitted. Tables 3, 4, and 5 list the key technical specifications for electric buses with battery swapping, regular charging, and fast charging, respectively. In this article, fast charging denotes charging completed in approximately 30 minutes. It is worth mentioning that these specifications are obtained from the announcements of bus manufacturers. It is

Table 3. Major specifications from certain models with battery swapping.

Company location		AVS USA	Foton China	Sunwin China
Vehicle	model	6.7m	BJ6123	SWB6121EV2
	length		12 m	12 m
	seats	22	50 (?)	32
	range	72–97 km	150 km	150 km
	price	$160K	¥1.2M	¥2M
Battery	type	Lead–Acid	Li	LiFePO4
	capacity	200–400 Ah	N/A	255 Ah
	packs	2–4	10	9
Charger	power	N/A	9 KW	9/30 KW
	time	6–8 hr	2 hr	3 hr
	price	N/A	N/A	N/A

Sources. AVS: Battery information from EPRI (1998); and others from Argonne National Laboratory (1997); Foton: Information from Foton (2013a) and Foton (2013b); and seat information includes standing passengers; Sunwin: Battery type and capacity, charger power, and charging time from Cai (2012a); and others from Sunwin (2013).

Table 4. Major specifications from certain models with fast charging.

Company location		Ebus USA	Hengtong China	HHI & Hankuk Fiber Korea	Optare UK	Proterra USA	Wampfler & Partners Germany
Vehicle	model	6.7m	CKZ6127	11m	Versa EV	EcoRide	7.5m
	length		12 m		11 m	10.7 m	
	seats	22	19−45	23	34	37	15
	range	72 km	40−50 km	80−110 km	?	48+ km	?
	price	$295K	￥1.7M	N/A	N/A	$1.2M	N/A
Battery	type capacity	NiCad 28 KWh	LiTi 140Ah	Li-poly 102 KWh	LiFeMgPO4 N/A	LiTi 72 KWh	Lead-Gel 180Ah
Charger	power	90KW	2×400KW	200KW	50KW	500KW	60KW
	time	30min	10min	20min	40min	10min	a few min
	price	$58K	￥500-600K	N/A	N/A	$1M	N/A

Sources. Ebus: Battery capacity from Chambers (2012); and others from Ebus (2013); Hengtong: Bus price from EV Times (2012); charger price from Jiang (2012); and others from Hengtong (2013); HHI and Hankuk Fiber: Charger power from Hyundai (2012) and Choi, Jeong, and Jeong (2012); range from Kim (2011); and others from Seoul Metropolitan Government (2012); Optare: Charging time from Midlands Business News (2013); vehicle size and seats from Optare (2012b); charging powerfrom ABB Terra 51 ABB (2012); range not mentioned given the 40-minute charging; and total £996,444 for six hybrid buses and three electric buses in Coventry (UK Department of Transport, 2013); Proterra: Battery capacity from Chambers (2012); battery type and seats from Quick (2010); charger power from Goldman (2010); charger price estimated from Chambers (2012) and Quick (2010); and others from Proterra (2013a); Wampfler & partners: All from Wampfler (2013b); the range of 200 km denoting the daily operation, and the range between charging not mentioned.

likely that some parameters have noticeable differences from real-world operations, for example, the operational range. In addition, the vehicle price is only a reference value since it is expected to vary by region.

3. Certain issues that influence the range

In this section, we discuss certain issues that influence the operational range based on experiences from real-world operations.

3.1 *The impact of air conditioners on the range*

The operational range is heavily influenced by the use of air conditioners. At the Shanghai Expo in 2010, an operational range of 250 km was demonstrated with air conditioners turned off, while the operational range of 150 km was demonstrated with air conditioners turned on (United Nations Environment Programme, 2009). The operations in Alabama also show that the operational range is reduced from a range of 129 to 145 km to a range of 80 to 96 km if the air conditioning is on (Williams, 2002). In both cases, air conditioning can consume more than 30% of the energy. Unfortunately, the operational range with air conditioning turned on is rarely mentioned in manufacturers' announcements. It was reported that the majority of electric buses used in the 1990s utilized another fuel to power air conditioners (see p. 3−4 in EPRI, 1998). Such a strategy is certainly an effective way to reduce the impact of air conditioners; however, depending on the alternative fuel, add emissions can be indirectly produced.

3.2 *The impact of driving behavior on the range*

Because sudden accelerating and decelerating can greatly increase fuel consumption of internal combustion engine vehicles, the range of electric buses is also greatly impacted by quick accelerating and decelerating. The key to taking advantage of regenerative braking is good driving behavior, in particular slow and even acceleration. Because buses need to stop frequently to serve passengers, there is a great deal of acceleration and deceleration. Therefore, slow acceleration and deceleration is especially important. It is reported that good driving behavior can improve the range by 30% or more (see p. 3−3 in EPRI, 1998). In fact, a driver energy system has been implemented in Santa Barbara to track the driving behaviors of bus drivers (Griffith & Gleason, 1996).

3.3 *Battery issues*

As a critical component of battery-electric buses, it is not surprising that the majority of issues are related to

Table 5. Major specifications from certain models with regular charging.

Company location		Ankai China	BYD China	DesignLine USA	Liotech Russia	Optare UK	OTOKAR Turkey	PVI France
Vehicle	model	HFF6121G03EV	K9	Eco-Smart I	TROLZA-52501	Solo EV	Doruk Electra	OREOS4X
	length	12 m	12 m	10.7 m	11.68 m	9.0-9.7 m	9 m	9.3 m
	seats	31−40	27 + 4	42	98 (?)	28−37	25	25
	range	250 km	250 km	193 km	120 km	129−161km	280 km	140 km
	price	N/A	￥2M	N/A	N/A	N/A	N/A	N/A
Battery	type capacity	LiFeMgPO4 400 Ah	Fe 600 Ah	Zebra N/A	Li-ion N/A	LiFeMgPO4 N/A	LiFeMgPO4 N/A	Li-ion 170 Ah
Charger	power	N/A	60/100 KW	N/A	90 kW	3 phase	3 phase	No
	time	4 hr	5/3hr		3 hr	6 hr	6−8 hr	6−8 hr
	price	N/A	N/A		N/A	N/A	N/A	N/A

Sources. Ankai: Seat and charging time from China Bus (2013); others from Ankai (2013); BYD: Price from Long & Wang (2012); range from BYD (2012a); and others from BYD (2012b). 27 + 4 denotes 27 seats and 4 foldable; DesignLine: All from DesignLine (2010); Liotech: All from Liotech (2013); seat including standing passengers; Optare: Charging information from (EV World, 2009); others from Optare (2012a); and total £760,320 for eight electric buses in Nottingham (UK Department of Transport, 2013); OTOKAR: All from Otokar (2012); PVI: All from PVI (2011); on-board charger.

(a) Full view (b) Inside the station

Figure 2. A battery swapping and recharging station in Qingdao, China.

batteries. The most common complaint heard may be the mismatch between the announced and actual operational ranges. For example, in Shenzhen, China, the actual operational range of an electric bus is about 180 km, which is much lower than the announced 250 km (Sun, 2012). The operational range can also decrease after electric buses have been used for some time. Shu (2012) reported that the operational range of electric buses is significantly reduced in Chengdu, China, after one year in operation. LINK Transit in Wenatchee, Washington, noticed the problem of leaky batteries (Pratt, 2011b) before the real operation. In fact, battery-electric buses had not been in operation yet in LINK Transit as of December 2012 (DeRock, 2012). Battery overheating is another problem, as experienced by Savannah, Georgia (p. 5−100 in EPRI, 1998).

4. Range remedy methods and analysis

The major disadvantage of battery-electric buses may be the relatively short operational range relative to conventional diesel buses. Griffith & Gleason (1996) show that two thirds of the buses travel less than 258 km every day in Santa Barbara. With current manufacturing and battery technology, an electric bus is often incapable of finishing a whole day's work without battery recharging. In this section, we will analyze the strengths and weaknesses of each range remedy method and conduct macroscopic analyses for cost, emissions, and charging impacts on the electric grid.

4.1 *Range remedy methods*

In order to remedy the short range, three methods have been proposed: (a) battery swapping; (b) fast opportunity charging during the layover period; and (c) regular (slow) battery charging with backup vehicles.

4.1.1 *Battery swapping*

Battery swapping has been widely used in Chattanooga (Dugan, 1994), Beijing (Beijing Municipal Commission of Transport, 2012), Shanghai (Cai, 2012a), Qingdao, and other cities. Figure 2 presents full and inside views on a battery swapping and recharging station in Qingdao, China. The major advantage of battery swapping is its ability to effectively extend the operational range. An electric bus is renewed after battery swapping. In addition, swapped batteries can be charged at night, thereby saving electricity costs and reducing impacts to the electric grid.

However, there are some serious weaknesses to battery swapping. A major disadvantage is the land-use issue. A battery-swapping station for buses is much more spacious than a swapping station for automobiles. Extra areas are also needed if some parking spaces are planned for bus waiting. In addition, certain areas are needed to install recharging racks. A battery-swapping station in Qingdao has an area of 5800 m^2 (Zhou, 2012). It is often difficult to find an appropriate area for a battery-swapping station in very urbanized areas. Building a battery-swapping station is also expensive. It cost $4.2 million in Chattanooga

(a) Pomona Station, Los Angeles (b) Namsan tower bus station, Seoul, Korea

Figure 3. Battery fast charging.

(a) Full view (b) Charging in progress

Figure 4. A battery fast-charging station in Chongqing, China.

(Argonne National Laboratory, 1997). Another important disadvantage is the need to purchase additional batteries that are necessary to exchange with ones near depletion. Purchasing these additional batteries is generally a large capital investment.

4.1.2 *Fast opportunity charging*

Fast charging has been used by Foothill Transit of Los Angeles (Foothill Agency, 2010), Chongqing, China (Hengtong, 2013), Seoul, Korea (Seoul Metropolitan Government, 2012), and other cities. Figure 3 shows the fast-charging stations in Los Angles and Seoul, and Figure 4 shows full and inside views of a fast-charging station in Chongqing. As can be seen from these figures, a fast-charging station generally requires much less land than a battery-swapping station. Such an advantage is very important since land is generally a very scarce resource in urbanized cities that are the main clients of battery-electric buses.

However, fast charging also has some weaknesses. The first weakness is the relatively short additional range relative to electric buses with battery swapping or regular charging. For example, the buses manufactured by Proterra and Hengtong can be charged in 10 minutes, but the added operational range is only about 48 km. It is likely that some bus routes require much longer distances. Electric buses with fast charging are not suitable for these long bus routes. The second weakness is the difficulty in utilizing discounted electricity rates, which are often applicable at night. Another weakness is the cost of buying expensive chargers, because for fast-charging buses such chargers generally have greater power and thus are expected to be much more expensive (see Table 4).

4.1.3 *Regular charging*

Regular charging has been used in Santa Barbara (Griffith & Gleason, 1996), Shenzhen (She, 2013), some cities in the UK (UK Department of Transport, 2013), and other cities. Figure 5 shows a regular charging station in Shenzhen, China. The land use is often not a major problem for regular charging, because a station can be located out of the Central Business District. The depot for diesel buses is a good candidate for the charging station. In addition, electric buses can be charged at night, thereby saving electricity costs.

However, an electric bus has to return to the charging station before its batteries completely discharge. If this electric bus has not finished a whole day's work, another bus has to be dispatched to serve remaining trips. Therefore, additional electric buses are often needed in order to overcome the short operational range, which is a major weakness associated with regular charging.

4.1.4 *Summary*

Table 6 lists the major strengths and weaknesses of different range remedy methods.

4.2 *Macroscopic cost analysis*

In this section, we conduct a macroscopic cost analysis for diesel buses, CNG buses, hybrid-diesel buses, electric buses with swapping, electric buses with fast charging, electric buses with regular charging, and trolley buses.

It is shown that it costs about \$320K, \$342K, and \$532K to purchase a diesel, CNG, and hybrid-diesel bus, respectively (Figure 1 in Clark, Zhen, Wayne, & Lyons, 2007). The procurement cost of an electric bus varies by charging method. For example, the cost with battery swapping by Foton can be about ¥1.2M (Foton, 2013a and Foton, 2013b); the cost with fast charging by Proterra can be about \$1.2M (Chambers, 2012 and Quick, 2010); and the cost with regular charging by BYD can be about ¥2.0M (Long & Wang, 2012). The purchase cost of a trolley bus can be about \$1.285M (King County METRO, 2011).

Diesel, CNG, and hybrid-diesel buses do not rely on chargers so the charger cost is zero for such vehicles. Battery-electric buses have to be recharged by a charger. However, there are very limited data published about the price of a charger. Based on the information from Chambers (2012) and Quick (2010), it can be estimated that it costs about \$1M to purchase a charger for fast-charging electric buses manufactured by Proterra.

Figure 5. Regular charging in a service station in Shenzhen, China.

Table 6. A summary of strengths and weaknesses of different range remedy methods.

	Strengths	Weaknesses
Battery swapping	1. Range anxiety is effectively solved. 2. Batteries can be charged overnight by taking advantage of discounted electricity rates. 3. Charging overnight can reduce impacts on the electricity grid.	1. The land for building battery swapping stations is spacious and may be difficult to find in very urbanized areas. 2. Constructing battery swapping stations is an expensive capital investment. 3. Purchasing additional batteries is an expensive capital investment.
Fast charging	1. It is not necessary to build a spacious battery service station. 2. It is easy to mount fast battery chargers in an existing bus station.	1. The operational range is relatively short, thereby (a) leading to more charges, and (b) not suitable for long bus routes. 2. It is difficult to take advantage of discounted electricity rates at night. 3. Chargers are more expensive due to larger power requirements.
Regular charging	1. It is not necessary to find sites for swapping or fast charging stations. 2. Batteries can be charged overnight by using discounted electricity rates. 3. Charging overnight can reduce impacts on the electricity grid.	1. Additional buses are needed for backup because buses must return to the charging station due to limited operational range. 2. Purchasing additional vehicles is an expensive capital investment.

We now discuss the energy cost for different types of buses. It is shown that fuel economy, in units of km per gallon, can be approximately 5.6327 for a diesel bus (Cohen, Hammitt, & Levy, 2003), 5.2626 for a CNG bus, and 7.3708 for a hybrid-diesel bus (Clark et al., 2007). The fuel price can be estimated as \$2.10 per gallon for CNG and \$3.99 per gallon for diesel (U.S. Department of Energy, 2013). Therefore, the energy cost, in units of cents per km, is about 70.84, 39.90, and 54.13 for diesel, CNG, and hybrid buses, respectively. The energy cost for electric buses depends on the electricity cost, the range in one charge, and electricity consumption in one charge. The electricity cost for transportation is about 10.26 cents per kWh (Energy Information Administration, 2013). The range and charging data can be found in Tables 3 through 5. The energy cost, in units of cents per km, can then be estimated as 12.31 for battery swapping, 17.81 for fast charging, and 12.31 for regular charging. Note that when the price is calculated for battery swapping, we have to consider the size of the battery pack (e.g., 10 packs in an electric bus by Foton). A trolley bus in San Francisco as part of the San Francisco Muni fleet can consume about 6.1 kWh per mile (Brown, 2011). We can then estimate that the energy cost of a trolley bus can be 39.12 cents per km.

Table 7 summarizes cost information; however, these data just provide approximate cost estimation at a macroscopic level. For example, the vehicle purchase cost can vary across countries. The life cycle of a trolley bus can be as long as 20 years, which is much longer than the life cycle of a diesel bus, about 12 years (King County METRO, 2011). Infrastructure cost is also significantly different among different types of buses. For example, electric buses with battery swapping often need a large amount of land to build the battery service center, which is expensive and often difficult to do in a central business district. Trolley buses need to get energy from overhead cables, which are very expensive to build. Energy cost is presented in terms of cents per km in Table 7. However, energy cost is also influenced by the range of a transit bus (Li, 2014). Therefore, the data presented in Table 7 should be seen as an approximate macroscopic estimate.

A major advantage of battery-electric and trolley buses is that they produce zero vehicle emissions. By comparison, CO_2 that is generated by diesel, CNG, and hybrid-diesel buses is 1,739 g/km (Cohen et al., 2003), 1,354 g/km, and 1,161 g/km (Clark et al., 2007), respectively. In this article, we do not monetize emissions as social costs, because as argued in Levy (2003), many of the uncertainties are not addressed in the current literature when estimating social damage costs.

4.3 Charging impacts on the electric grid

We now discuss the potential impacts on the electric grid of charging electric buses. Electric buses with battery swapping and regular charging can be charged at night; the impact on the electric grid may be negligible during such off-peak hours. We then focus on examining the impact of fast-charging electric buses on the electric grid. Let us use the Los Angeles metropolitan area as an example. As one of the largest transit agencies in the United States, LA Metro operates about 189 bus routes (see http://www.metro.net). The majority of bus routes have two directions. We now consider a worst-case scenario: all the buses in these directional routes are being charged simultaneously, which means that the electric grid is charging 378 buses at the same time. Such a situation rarely occurs in the real-world because it is unlikely for all the bus routes to request simultaneous charging.

Table 7. A macroscopic average cost analysis.

	Vehicle cost	Charger cost	Energy cost (unit: cents per km)
Diesel	\$320K	0	70.84
CNG	\$342K	0	39.90
Hybrid diesel	\$532K	0	54.13
Electric-swapping (based on Foton)	￥1.2M	N/A	12.31
Electric-fast charging (based on Proterra)	\$1.2M	\$1.0M	17.81
Electric-regular charging (based on BYD)	￥2.0M	N/A	12.31
Trolley	\$1.285M	N/A	39.12

The charger for fast-charging electric buses has high power, e.g., 500 kW (see Table 4). Therefore, in the worst case, the total load is 500 kW $\times$ 378, which is about 189 MW. Currently, Los Angeles Department of Water and Power can deliver 7,200 MW of electricity (Beshir, 2007). Even in the worst case, fast-charging electric buses consume about 2.6% of total power capacity, which is insignificant. Therefore, the impact of fast-charging electric buses on the electric grid may not be an important issue because the total demand is small.

5. Conclusion

Battery-electric buses have been operational since as early as 1907 in London. Operations in Santa Barbara and Chattanooga from the early 1990s have proven to be very successful. In recent years, the development of battery-electric buses with the aim of mitigating air pollution has received worldwide attention. Most manufacturers focus on building heavy-duty electric buses (say about 11 m) instead of medium-sized buses (say about 6.7 m) widely used before. In addition, a few manufacturers have developed electric buses with fast charging in 10 minutes. Some cities across the world are operating or plan to operate battery-electric buses on a large scale, with more than a few hundred buses. In this article, we have attempted to provide a review of electric bus developments and operations. We summarize the experiences and lessons learned from real-world battery-electric bus operations. We also present key technical specifications that are critical to operations of electric bus systems.

Battery-electric buses suffer from a major disadvantage: the operational range is generally not long enough for whole-day service. In order to overcome the limited operational range, three range remedy methods have been proposed: (a) regular (slow) battery charging and having additional fully charged buses as backups; (b) battery swapping in which fully charged batteries are exchanged with existing batteries from the service bus; and (c) fast opportunity charging generally completed in no more than 30 minutes at the final stop during a layover period. We conduct a qualitative analysis on the strengths and weaknesses of each range remedy method. We also analyze the vehicle cost, energy cost, and emissions of transit buses powered by different sources, and examine potential impacts of fast-charging electric buses on the electric grid.

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