Advantage and feasibility of wireless charging electric bus systems

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Abstract—The electric vehicles can be charged through plug-in chargers but there are challenges such as heavy battery packs (e.g. electric buses with large batteries), and high battery costs. An alternative charging method of wireless charging where wireless power transfer technology is applied may overcome the problem with plug-in charging. Due to limited operational ranges of battery-electric buses, two range remedy methods are available: (a) regular plug-in battery charging with backup vehicles; (b) en-route wireless charging during service where wireless charging takes place while a bus is loading and un-loading passengers. Thus, costly backup vehicles could be eliminated and battery packs can be downsized as well. This paper compares two charging scenarios plug-in charging and stationary wireless charging for all-electric bus systems and compare them to conventional diesel buses, with respect to costs, battery downsizing potential and energy consumption rates. A model is developed to evaluate plug-in and wireless charging electric bus systems and conventional diesel bus systems. A city's transit bus system is selected for a case study on the plug-in charging and stationary wireless charging systems, together with diesel buses. The plug-in charging and stationary wireless charging systems are modelled through the case study. The wirelessly charged battery for electric buses can be downsized by 46% of the plug-in charged battery, thus significantly decreasing the cost and weight of battery packs for electric buses. Energy consumption rates for wirelessly charged buses also decrease, resulting from reduced bus weight. Simulation results showed that if 10% vehicle mass reduction is achieved by implementing wireless charging, energy consumption of electric buses can be reduced by 5.5%. In addition, wireless charging systems have the advantages of increased safety and city aesthetics, and the potential to make road transportation more intelligent.

Keywords—Wireless charging, electric vehicles; battery; economic feasibility

I. Introduction

Electric vehicles (EVs) are leading clean technology with low emissions for road transportation. However, due to shortcomings such as insufficient charging infrastructure, limited battery capacity, and long charging time, the adoption and diffusion of electric vehicle technology have been limited so far. EVs can be charged through plug-in chargers but there are challenges such as heavy battery packs (e.g. electric buses with large batteries), and high battery costs. Heavy battery pack is a challenge for further improving vehicle energy consumption, especially for all-electric buses. The battery pack can comprise about 30% of the weight of bus. Lithium iron phosphate (LFP) battery cost can account for a substantial portion of the cost of an electric bus. An alternative charging method, EV wireless charging, an application of the wireless power transfer (WPT) technology, may overcome the problem with plug-in charging. Wireless charging electric vehicles (WCEVs) have the potential to make road transportation more intelligent.

The theoretical basis of wireless charging technology is WPT. In the field of electric vehicles, the wireless charging mainly denotes medium-range WPT, through near-field (non-radiative) electromagnetic coupling [1, 2]. By the form of energy transfer, WCEVs technology is categorized into two types: capacitive wireless charging electric vehicles and inductive wireless charging electric vehicles. For the latter, the electric energy is transferred wirelessly through magnetic field between two coil plates, one loaded on the bottom of the vehicle and the other embedded in pavement. Capacitive WCEVs have development potential, especially in the field of dynamic WCEVs [1, 3]. Capacitive WCEVs have two kinds of advantages. Firstly, capacitive WCEVs do not require ferrite cores. The cost of the coupler is low, and the size is small [4]. Secondly, without the limitation of ferrite cores loss, the system power can be set very high to improve energy transfer efficiency [5]. However, slow development of high-performance materials poses barriers for capacitive WCEVs [5, 6].

A number of research institutions are investing in WCEVs research. For instance, the University of Auckland started inductive energy transfer research in the 1990s and applied wireless charging technology to electric cars in the materials handling industry [7]. The University of California, Berkeley led the Partners for Advanced Transit and Highways (PATH) project to develop the first prototype of the wireless charging electric vehicle [8]. In 2009, Korea Advanced Institute of Science and Technology (KAIST) [9] developed the first commercially available dynamic wireless charging electric bus named on-line electric vehicle [10, 11]. Oak Ridge National Laboratory (ORNL) [12], with the support of the US Department of Energy, has been implementing the WCEVs research and development of static passenger vehicles, opportunistic charging (transport/shuttle), and dynamic charging since 2012. Utah State University [13] has been implementing the Sustainable Electrified Transportation Center project since 2016 to validate and promote the commercialization of WCEVs.

Considering application scenarios of electric vehicles and the size of electromagnetic couplers, inductive wireless charging technology is considered the first choice for WCEVs [1, 14]. In recent years, stationary inductive WCEVs have achieved significant progresses [15].

By the charging application scenarios, each WCEVs technology can be grouped into stationary charging and dynamic charging [16, 17]. Stationary wireless charging (Figure 1) can be installed in a garage, parking lot or bus stop [16]. For dynamic charging, the vehicle can be charged in motion through multiple sets of coils and accessories embedded along the road. The charging efficiency of more than 85% has been reported for both stationary and dynamic charging. Wireless charging provides frequent charging opportunities at transit centers and major bus stops, resulting in battery downsizing, vehicle light weighting and energy consumption improvement, as compared with plug-in charging. As a result, WCEVs have benefits of downsizing the battery and reducing the battery costs and increasing safety and city aesthetics. Figure 2 shows a wireless charging electric bus. However, the wireless charging infrastructure brings additional costs of charger procurement and installation. Therefore, there are still uncertainties associated with the application of WCEVs. The engineering side of EV wireless charging has been investigated widely, but the overall evaluation and comparison between plug-in and wireless charging systems have not been well performed.

From another viewpoint, due to limited operational ranges of battery-electric buses, there could be two range remedy methods: (a) regular battery charging with backup vehicles; (b) en-route wireless charging during service where wireless charging takes place while a bus is loading and unloading passengers.

This paper aims to compare two charging scenarios for all-electric bus systems, i.e. plug-in charging and stationary wireless charging, together with diesel buses, in terms of cost, battery downsizing potential and energy consumption rate. A model is developed to evaluate these bus systems. The plug-in charging and stationary wireless charging electric bus systems and diesel buses are modelled through a case study on a city's transit bus system.

Figure 3 shows plug-in charger and wireless charger approaches for electric vehicles [18]. The dashed box represents on-board portion of the charger and the rest is outside the vehicle. The components in grey show the difference in equipment between the two EV charging approaches.

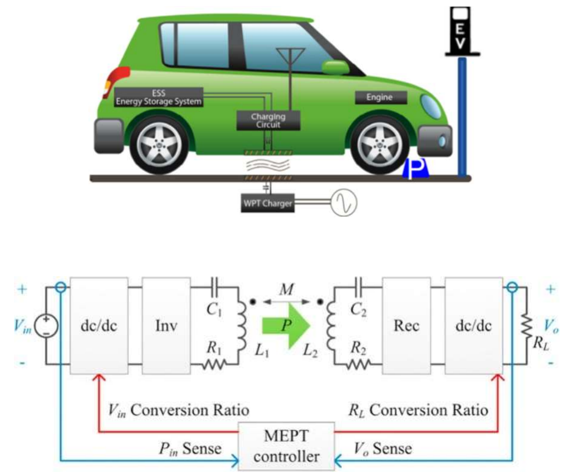

Figure 1. Concept of stationary charging EV [16]. MEPT: Maximum efficiency point tracking.

Figure 2. A wireless charging electric bus

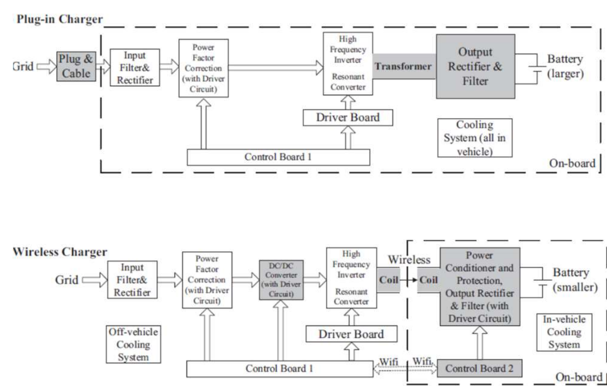

Figure 3. Schematic diagram of plug-in charger and wireless charger for electric vehicles [18].

I. METHOD

A. *Description*

The goal of this study is to compare two charging scenarios for all-electric bus systems, plug-in charging and stationary wireless charging and conventional diesel buses, regarding cost, battery downsizing potential and energy consumption rate. A model is established to evaluate the two charging systems. An important and busy transit bus transportation system that serves Bayshore-Parliament/Rideau/Lees in Ottawa city, via both Lincoln Field and Queensway (Figure 4), has been selected for the case study simulation. The numbers of routes, buses and bus stops are adapted from the known information.

Figure 4. Bus routes of interest in Ottawa city that serves Bayshore-Parliament/Rideau/Lees, via both Lincoln Field and Queensway

The adapted bus system map and the modeling parameters can be found in the OC Transpo bus routes times and schedule information. Here, 36 buses, 6 routes and 80 bus stops are identified in the bus system for the case study. Two charging cases are modeled: (1) plug-in charging and (2) stationary wireless charging. For the former case, the plug-in chargers are located at the parking places for buses to charge overnight. For the latter case, the wireless charging infrastructure are installed across the bus service routes at the certain bus stops, transit centers and the overnight parking places. Considering possible charging times at transit centers and busy bus stops, 28% of the operation time are assumed to be available for wireless charging during the bus operation periods.

B. Model

To examine the economic feasibility of the wireless charging system, the costs of plug-in charging bus system versus wireless charging bus system are evaluated using the following model. The total cost of a stationary wireless charging system is calculated from:

$$C_{wtotal} = \sum_{i=1}^{6} C_{wi} \quad (1)$$

where C_{w1}, C_{w2}, C_{w3}, C_{w4}, C_{w5}, C_{w6} are the cost of electric bus, the battery cost, the cost of wireless charger, the cost of wireless charge installation, the electricity cost and the maintenance cost, respectively.

The total cost of plug-in bus system is:

$$C_{ptotal} = \sum_{i=1}^{6} C_{pi} \quad (2)$$

where C_{p1}, C_{p2}, C_{p3}, C_{p4}, C_{w5} C_{w6} are the cost of electric bus, the battery cost, the cost of pug-in charger, the cost of wireless charge installation, the electricity cost and the maintenance cost, respectively.

The total cost of traditional diesel bus system is:

$$C_{dtotal} = \sum_{i=1}^{3} C_{di} \quad (3)$$

where C_{d1}, C_{d2}, C_{d3} are the cost of internal combustion engine bus, the diesel cost the maintenance cost, respectively.

TABLE 1. THE PARAMETERS AND VALUES USED IN THE CALCULATION OF BATTERY DOWNSIZING DUE TO WIRELESS CHARGING

Parameter	Value	Unit
C_{or}	495	kWh
E_{ot}	265	kWh
S_{cr}	90	%
P_e	65	kW
e_i	5.5-32.5	kW
η	90	%
n	80	-

The wireless battery in electric buses can be downsized due to wireless charging availability at a number of charging stations during bus operation and services. In other words, the bus can charge at each of those stations. Thus the bus can carry a smaller battery to travel the same distance than the plug-in charging, resulting in the capacity reduction for wireless charging scenario. The battery downsizing may be calculated as follows. C_a (kWh) is defined to be the battery capacity after capacity reduction.

$$C_a = \frac{C_{or} - E_{ot}}{S_{cr}} \quad (4)$$

$$E_{ot} = \sum_{i=1}^{n} e_i = \eta P_e t \quad (5)$$

where C_{or} (kWh) is the minimum plug-in battery electricity amount requirement at start of each day for a bus; E_{ot} is the total amount of electricity charged during operation time (hours); S_{cr} is so-called state of charge range (%) that is defined as the percentage of the C_{or} relative to the whole capacity of a new battery (kWh); e_i (kWh) is the amount of electricity charged at charging stop *i*, *n* is the total number of stops for charging, η (%) is the average charging efficiency, P_e (kW) is the charging power and t is the total charging time at charging stops during the day. Table 1 shows The parameters and values used in the calculation of battery downsizing due to wireless charging

II. RESULTS

A. Cost analysis

In this study, we have calculated the lifetime costs of plug-in electric bus, diesel bus, and stationary wireless charging bus systems for selected transit bus routes in Ottawa city, which are Bayshore-Parliament/Rideau/Lees, via both Lincoln Field and Queensway. Figure 5 shows the calculated results. For a period of 12 years, the lifetime cost of the wireless charging system is $44.54 million while the lifetime cost of the plug-in bus system is $47.32 million, and the lifetime cost of the diesel bus system is $60.08 million. The stationary wireless charging electric bus system turns out to be the most cost-effective. This is mainly due to the fact that the wireless charging system has the lower battery cost. On the other hand, the operational range of plug-in charging electric buses is not enough for a full day operation and thus backup buses are needed. In this case, the cost would be even higher. For instance, if 12 backup buses are considered, another \$6.2 million will be cost for the plug-in charging bus system.

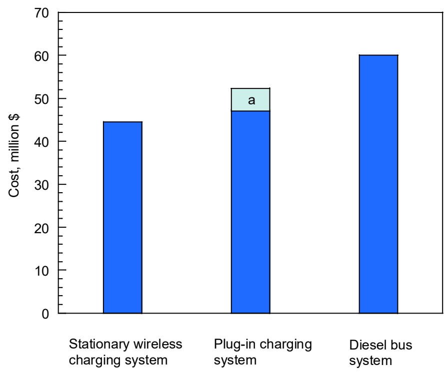

Figure 5. Lifetime costs of wireless charging bus, plug-in bus and diesel bus systems. a stands for the cost of backup electric buses.

Figure 6 shows the breakdown of the lifetime costs per km/bus of the wireless charging, plug-in charging and diesel bus systems. The costs per km/bus for the wireless charging, plug-in charging and diesel bus systems are \$0.78, \$0.83, and \$1.06 per km/bus, respectively. It is noted that wireless batteries cost less than plug-in batteries. However, infrastructure costs for wireless charging, including procurement and installation of chargers are higher. Calculations show that the infrastructure costs 0.95 cent per km/bus for plug-in charging, but the cost rises to 2.25 cents per km/bus for wireless charging.

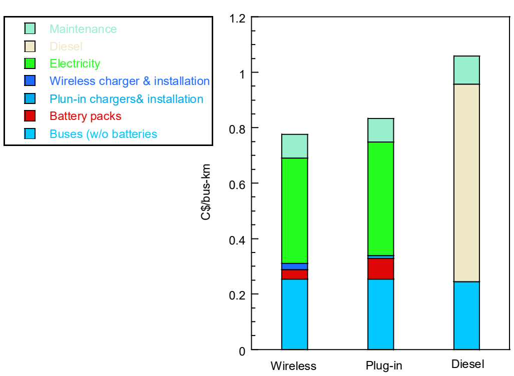

Figure 6. Costs per bus-km of plug-in electric bus, wireless charging electric bus, conventional diesel bus

It should be noted that, as time progresses, the price of electric vehicle batteries will have decreasing. This may lead to the cost advantage of the wireless charging lessening. However, wireless charging still has many advantages over plug-in charging. For instance, wireless chargers can be installed at bus stops and transit centres without losing city's aesthetics where the installation of plug-in chargers is not possible.

B. Energy consumption

Researches on energy consumption were mainly focused on conventional vehicles. Recently, these researches have been extended to the energy use of EVs, including development of energy models, assessment of the influences on the energy consumption, and global energy consumption or grid impact due to the introduction of EVs. The methodology for the calculation of energy consumption consists of creating a vehicle model that simulates electrical parameters based on kinematic and dynamic requirements or by means of statistical models. The energy consumption considered in this study is the energy consumption on a battery-to-wheel scope, corresponding to the energy drawn from the battery. The battery-to-wheel consumption is a function of the required mechanical energy. The total required mechanical energy as a function of the kinematic parameters can be calculated from the vehicle dynamics equation [19]:

$$E_{ij} = 3600^{-1} d_{ij} \left[M_{ij} g(f \cos\theta + \sin\theta) + 0.039 \rho C_d A V_{ij}^2 + \left(M_{ij} + M_f\right) \frac{dV}{dt} \right] \quad (6)$$

In Equation (6):

E_{ij} is the mechanical energy required at the wheels to drive on a distance d_{ij}, kWh

M_{ij} is the total vehicle mass, kg

M_f is the fictive mass of rolling inertia, kg

G is the gravitational acceleration, m/s²

F is the vehicle coefficient of rolling resistance

θ is the road gradient angle, °

ρ is the air density, kg/m^3

C_d is the drag coefficient of the vehicle

A is the vehicle equivalent cross section, m^2

V_{ij} is the vehicle speed between the point i and the point j, km/h

d_{ij} is the distance driven from point i to point j, km

The factors affecting the energy consumption include the rolling resistance, potential energy, aerodynamic losses and energy for the acceleration of rotational parts. Equation (6) may be simplified as:

$$E_{ij} = B_{ij} M_{ij} + C_{ij} \quad (7)$$

where B_{ij} and C_{ij} are two coefficients. They are statistical coefficients that correlate the kinematic parameters over a trajectory and the measured energy consumption at the battery. If all the conditions of an electric bus in service are the same, the energy consumption will depend on the total vehicle mass. The battery downsizing results in a reduction in bus weight and thus improve the energy consumption. In other words, the battery electricity will deplete more slowly. Besides, a reduced bus weight consumes less energy in day-to-day service distance, this would give rise to further downsizing of the battery and thus improve further energy consumption rate. The battery or bus weight reduction is calculated from battery specific energy (e.g. 0.13kWh per kg of Li-ion battery). The gross weight of a typical plug-in electric bus is about 22000kg. In the present study, the battery weight is reduced by 2269kg, due to implementing wireless charging. That is about a 10% vehicle mass reduction. The energy consumption improvement resulting from the vehicle mass reduction can be calculated from Equation (6) or (7) where the parameters or coefficients can be obtained from specifics vehicle and concrete statistical data. Based on the data available at this time, a 10% vehicle mass reduction could lead to a 5.5% energy consumption reduction for electrical vehicles. The battery weights and energy consumption rates for plug-in and wirelessly charged buses are calculated and presented in Figure 7.

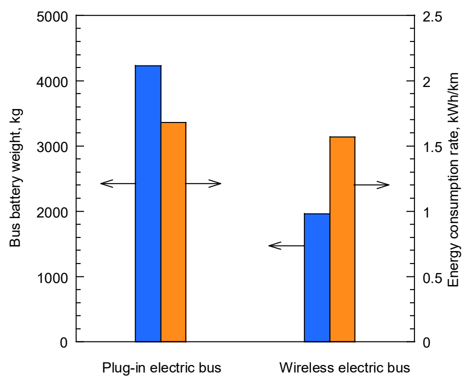

Figure 7. Battery weights and energy consumption rates for plug-in and wirelessly charged buses

III. SUMMARY

Plug-in charging and stationary wireless charging for all-electric bus systems as well as conventional diesel buses were compared regarding costs, battery downsizing potential and energy consumption rates. En-route wireless charging during service where wireless charging takes place while a bus is loading and un-loading passengers could be a solution to limited operational ranges of battery-electric buses. As a result, costly backup vehicles could be minimized or eliminated. A model was developed to evaluate plug-in and wireless charging electric buses systems together with diesel bus systems. The plug-in charging and stationary wireless charging systems were modelled through a case study. It has been shown that the wirelessly charged battery for electric buses can be downsized by up to 46% of the plug-in charged battery, thus significantly decreasing the cost of battery pack in electric buses. Simulations show the 12-years lifetime cost of a wireless charging system is $44.54 million while the cost of a plug-in bus system is $47.32 million, and the cost of a diesel bus system is $60.08 million for the case study on selected bus transit routes in Ottawa city. If backup buses for the plug-in charging bus system are included, another $6.2 million will be cost. Moreover, energy consumption rates for wirelessly charged buses decreases, result from reduced bus weight. Simulations also shows a 10% vehicle mass reduction achieved by implementing wireless charging could lead to a 5.5% energy consumption reduction for electric buses. This means that the electricity depletion rate of wirelessly charged batteries is lower than that of plug-in charged batteries. Note that the price of electric vehicle batteries has been decreasing as time progresses. In spite of this, wireless charging could still have certain advantages over plug-in charging. Wireless chargers can be installed at bus stops and transit centres where the installation of plug-in chargers is not possible. Also, wireless charging systems have the potential for AI access and assistance, increased safety and city aesthetics.

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