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Evaluation of a Commercial Demonstration Bus Line Utilizing Wireless Charging Technology

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ABSTRACT

This paper conducts an investigation on the operating cycle of Bus No. 306, which is equipped with wireless charging system, in Changsha, Hunan Province, China. The wireless charging system and electric buses are manufactured by ZTE Corporation (Zhongxing Telecommunication Equipment Corporation) and BYD Company Limited, respectively. In this paper, the operating cycle is quantified and modeled based on experimental data. The real-time bus route and SOC (state of charge) during daytime operation are recorded with the help of GPS (global position system) and BMS (battery management system). The wireless charging process is tested with a power analyzer and its charging efficiency is compared with a plug-in system. Besides, the radiation level while charging is also taken into consideration. Currently, the buses are designed to operate in daytime and get charged at night. In order to explore the battery downsizing potential, plug-in buses, wireless charging buses with fixed and free departure schedule are simulated and compared. As a result, extra charging opportunities are introduced to daily operation so that the rated battery capacity can be reduced by more than 70%.

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INTRODUCTION

Energy saving and emission reduction are becoming two of the most important issues for the next generation of powertrain. Gasoline engine can realize acceptable emission level with the help of TWC (three way catalysts) but its thermal efficiency is limited by high in-cylinder pressure rise rate. For diesel engine, fuel economy can be achieved because of its high compression ratio while extra after treatment system should be introduced to deal with HC and PM emission, which will bring high cost.

Vehicle electrification is another promising method to solve these problems. Electric vehicles (EVs) which are powered by rechargeable batteries has the potential to significantly reduce emissions compared to internal combustion engine vehicles [1]. Conventionally, electric vehicles are charged through plug-in chargers, which bring great challenges for commercialization, including heavy battery packs, high battery costs and limited time and opportunities for charging. Besides, the plug-in chargers have to be connected with vehicle manually. That is to say, high voltage equipment together with sleety weather can be a great threat to personal safety.

An alternative charging method, which is a kind of wireless power transfer (WPT) technology, is proposed to overcome the problems of plug-in charging. It is also known as wireless charging technology.

Wireless power transfer was first realized by Nicola Tesla, who introduced near-field coupling of two loop resonators based on magnetic resistance more than a century ago [2, 3]. Marin Soljacic et al made a breakthrough in electrical energy transfer in 2007. His team realized wireless power transfer via coupled magnetic resonances, during which a 60 watt bulb was lighted [4]. From 2012, low-power wireless charging equipment has been adopted in scale on small electronic devices, such as mobile phone.

High-power wireless power transfer is becoming more and more popular in the recent year. Many companies and research institutions planned to step into this area. Qualcomm's Halo group in England worked together with Auckland University in New Zealand on stationary wireless charging pads. Their "Double D" pads are claimed to have higher efficiency and able to deliver twice the power compared to circular pads [5]. In Nov. 10th, 2011, Qualcomm Incorporated announced their first wireless electric vehicle charging trail in Tech City, east London [6]. In the year of 2012, BMW and Nissan announced their project on automotive wireless charging and product development plan successively [7, 8, 9]. In 2014, a bus line utilizing wireless charging technology was put into commercialization in the London suburb. With the help of wireless charging technology, the electric vehicle can be charged through power transfer between two coils, the primary coil and pick-up coil, instead of plug-in chargers. Wireless charging can be classified into stationary and dynamic charging [10], of which the stationary charging equipment is utilized during the vehicles' parking period. At present, wireless charging technology is introduced mostly on vehicles with fixed routes, for example urban public bus line [11]. Wireless charging technology can provide more charging opportunities at the parking lot during bus operation hours. Thus the battery size and weight can be reduced, which results in vehicle light weighting and fuel consumption reduction.

ZTE Corporation (Zhongxing Telecommunication Equipment Corporation) is devoting itself to providing advanced wireless charging integrated solutions and service to automotive industry. ZTE developed its prototype wireless charging system in 2012. The system was installed and tested on a Dongfeng minibus in 2013 and passed the National Science and Technology Achievement Appraisal in the following year. In June, 2014, the first high-powered wireless charging demonstration bus line in the world was launched in Xiangyang, Hubei Province, China. The buses are modified from Dongfeng electric coaches and equipped with 30 kilowatts ZTE wireless charging systems, which is the first commercialized generation of ZTE wireless charging system and is known as ZXWPT030 (V1.0). As shown in Figure 1, ZTE have cooperated with more than 20 provinces and its WPT solution have been applied in at least 12 cities, including 13 cases, in China.

The second generation of wireless charging system (ZXWPT030) is applied to a commercial demonstration bus line in Changsha, Hunan Province, China. In this paper, the second generation of ZTE wireless charging system and the structure of its wireless power transfer solution will be introduced in detail. Then, the whole commercial operation cycle will be quantified and modeled with the help of test data. The battery downsizing potential of buses with wireless charging system under different schedules and that of plug-in electric buses are simulated and compared. Besides, further optimizing method is also proposed.

INTRODUCTION OF ZTE HIGH-POWERED WIRELESS CHARGING SOLUTION

Introduction of ZXWPT030

The tested ZXWPT030 system is the key part of the second generation of ZTE wireless power transfer solution for electric vehicles. The system converts electrical energy into electromagnetic energy and transmits it wirelessly to the electric vehicle terminal. Then the electromagnetic energy is converted into electric energy to charge the battery. The specifications of the second generation of ZXWPT030 is shown in Table 1. It is a kind of 30 kW high-powered wireless charging system, which is installed in parallel on the tested buses. However, the input power of the paralleled system is limited to about 42 kW in this case.

Figure 1. Application cases of ZTE wireless power transfer solution

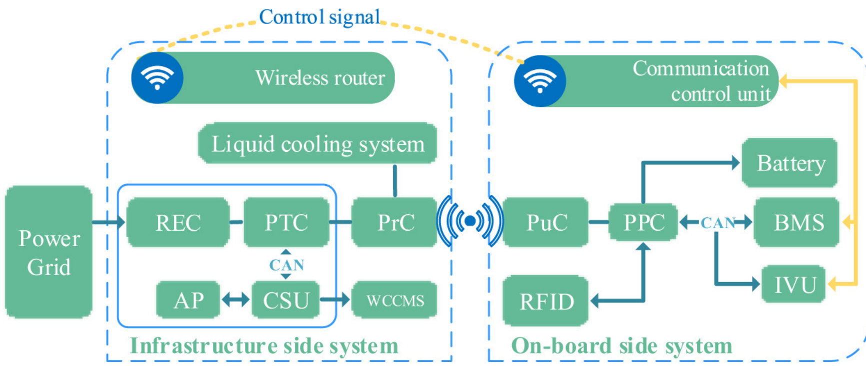

Figure 2. Structure of ZXWPT030 System

Table 1. Specifications of ZXWPT030

PrC (Primary Coil)	
Degree of protection	IP67
PuC (Pick Up Coil)	
Cooling method	Natural cooling
Degree of protection	IP67
Heat consumption	660 W
System Electrical Specifications	
Input voltage system	Three-phase five-wire system
Rated input voltage	380 V
Input voltage range	304 ~475 V
AC input frequency	50 Hz/60 Hz
AC frequency range	40 Hz ~70 Hz
Rated output power	30 kW
Rated output voltage	Output interface 1: 600 V
	Output interface 2: 27.5 V
Output voltage adjustable range	Output interface 1: 540 V ~ 630 V
	Output interface 2: 18 V ~ 32 V
Output current	50 A (Adjustable range: 5 A ~ 50 A)
System efficiency	Typical Value: 88% (Normally between 86~91%)

The structure of ZXWPT030 system is shown in figure 2. The rectifier (REC) on the infrastructure side is used to convert alternating current (AC) into direct current (DC). Power transmit control (PTC) unit is used to convert the DC output from REC in to high frequency AC and transmit it to the primary coil (PrC). On the vehicle side, pick-up coil can receive high-frequency electromagnetic energy emitted by PrC in the ground and convert it into high-frequency AC. The high-frequency AC is then converted to DC by power pick-up control (PPC) unit. The DC power is transported to the battery or other on-board loads. In vehicle unit (IVU) provides the interaction surface and control the entire charging process. Besides, it can complete the authentication of the charging module on the vehicle and charging facility on the ground. The radio frequency identification device (RFID) can help vehicle recognize the ground charging facility when approaching the charging position. Communication service unit (CSU) can communicate with IVU and assist to complete the identity authentication and information exchange between vehicle and payment carrier. Access point (AP) is used to assist the CSU in wireless communication with IVU. One or More IVUs can be connected in to the CSU network.

The entire structure of ZTE high-powered wireless charging solution is shown in Figure 3. The solution can be divided into four parts. They are on-board system (including on-board charging and control system as well as mobile Internet data interaction module), in-ground system (including in-ground charging and control subsystem as well as identification, alignment and security monitoring module), identification, security and billing control cloud and vehicle monitoring and management cloud.

Benefit from its rich technology accumulation on telecommunication, intelligent terminal and information technology, ZTE wireless charging solution is fully automatic, which can provide a collection of automatic charging, automatic billing, APP payment, cloud management, automatic operation and remote monitoring and other automatic terminal-to-terminal services for all kinds of users and managers.

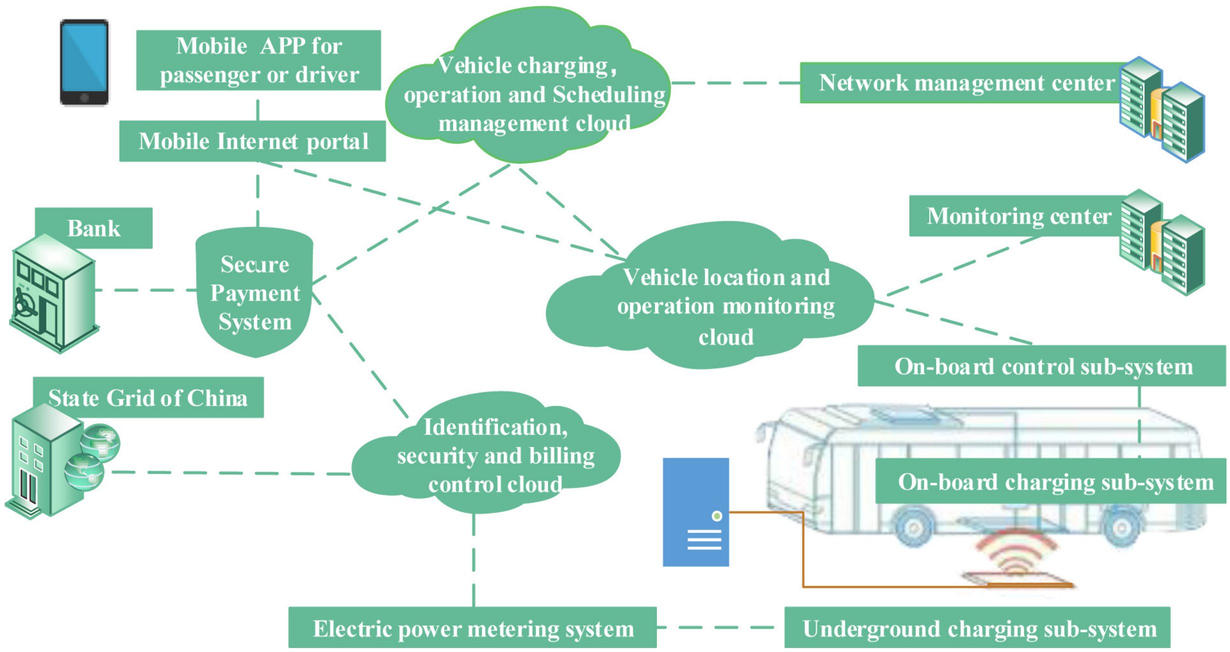

Figure 3. Topography of ZTE high-powered wireless charging solution

Introduction of Commercial Demonstration Bus

Figure 4 shows the commercial bus and charging lot. The picture on the left shows the appearance of the bus. In the middle picture, we can notice that there is a black and white bridge-like steel tube in the front. In addition, two white painting lines are connected with two terminals of the tube and perpendicular to it. The steel tube together with white painting lines serve as the boundaries of the charging lot. As shown in the right picture, when the bus front wheels press against the tube while the body is located between the painting lines, the bus can be identified and get charged. Two square covers shown in the middle picture are made of organic glass, under which lays two parallel installed PrCs.

Figure 4. Wireless Charging Bus and Charging Lot

The specifications of bus are listed in Table 2. It is BYD K8 electric bus. The motor and battery parameters are shown. It is a BYDTYC90A permanent magnet synchronous motor (PMSM) powered by lithium iron phosphate battery.

Table 2. Specifications of BYD K8 electric bus

Basic Parameters	
Vehicle model	CK6100LGEV1
Manufacturer	BYD AUTO INDUSTRY CO., LTD
Size	10490 mm×2500 mm×3150 mm
Curb mass	11100 kg
Maximum allowable mass	16700 kg
Passenger capacity	87/33
Driving range	≥200 km
Battery Parameters	
Battery type	Lithium iron phosphate battery
Battery manufacturers	Huizhou BYD Battery Co.
Rated voltage	720 V
Battery capacity	270 Ah
Motor Parameters	
Motor model	BYD-TYC90A
Manufacturer	BYD INDUSTRIAL CO., LTD
Motor type	PMSM
Rated power	75 kW
Peak power	90 kW
Maximum torque	350 N·m
Maximum motor	7500 rpm

Test Instruments Introduction

Table 3 lists the test instrument. ZLG PA2000mini Power Analyzer is used to monitor and record electrical indicators during charging process. Narda B-field meter and probe are used to measure magnetic induction distribution in and around the bus. V-990 GPS data logger can track the vehicle route. At the same time, vehicle path, speed, height, time and other indicators can be recorded.

Table 3. List of test instruments

Test Instrument	Manufacturer
ZLG PA2000mini Power Analyzer	Zhiyuan Electronics Co., Ltd
Narda ELT-400 Magnetic Field Meter	Narda Safety Test Solutions
Narda B-field ELT probe	Narda Safety Test Solutions
V-990 multifunction GPS data logger	Explorer™ Columbus

MAGNETIC EXPOSURE LEVEL TEST

High EMF (electromagnetic field) level may bring risks of transient neurological response, including stimulation of the peripheral nerve and central nerve system, retinal phosphene and other possible influences on brain functions. That is to say, extra charging opportunities during daytime operation can be available only if the magnetic exposure level can meet the requirements of EMF regulations. Thus, the influence of magnetic induction on human body should be evaluated firstly.

The magnetic exposure level on and around the bus is tested by Narda ELT-400 magnetic field meter according to the International standard IEC-TC69-PT61980 [12]. The technical standard IECTC69-PT61980, which covers general requirements for electric road vehicle wireless power transfer system, is published by the International Electro-technical Commission (IEC). IEC is a worldwide organization for standardization comprising all national electro-technical committees (IEC National Committees). Measurement frequency range is from 30 Hz to 400 kHz in accordance with IEC62233. The results are shown in Figure 5 and Figure 6.

Figure 5 shows the magnetic induction distribution around the vehicle. This measurement is done in nominal position in 3 height position 500 mm, 1000 mm and 1500 mm in accordance with IEC62110. In nominal position measurement, the secondary device shall be centered above the PrC. Front, rear, left and right points which have 200 mm distance to the vehicle body surface should be tested. In this case, the positions where to get on or off the bus are also tested. Results show that the place near the back door ground on the right side of the bus, where the PrC is installed below, has the highest magnetic induction level. The magnetic induction drops rapidly as away from the PrC. The maximal value around the vehicle is 2.530 μT, which is lower than the field limit 27 μT for general public exposure in accordance with the basic restriction from the ICNIRP Guidelines 2010 [13].

Figure 6, shows the magnetic induction distribution inside the bus when the bus is in nominal position. The measure is carried out in driver's seats and the closest seats to PuC in 2 height positions as high as chest and head of an adult. Results show that the area with the highest magnetic induction level is just over the PuC and the right side of the inside bus has higher level than the left side. Besides, we can notice that the higher the height is, the lower the magnetic exposure level will be. The magnetic induction in the driver's seat is 0.081 μT. The maximal value inside the vehicle is 0.322 μT, which is lower than the field limit for general public exposure in accordance with the basic restriction from the ICNIRP Guidelines 2010.

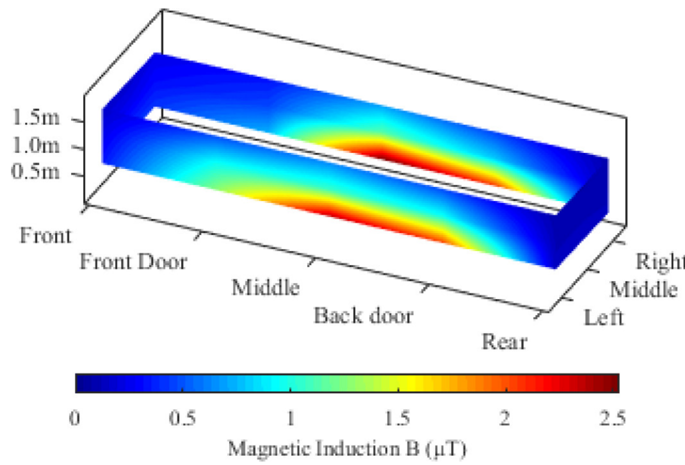

Figure 5. Magnetic induction distribution around the bus

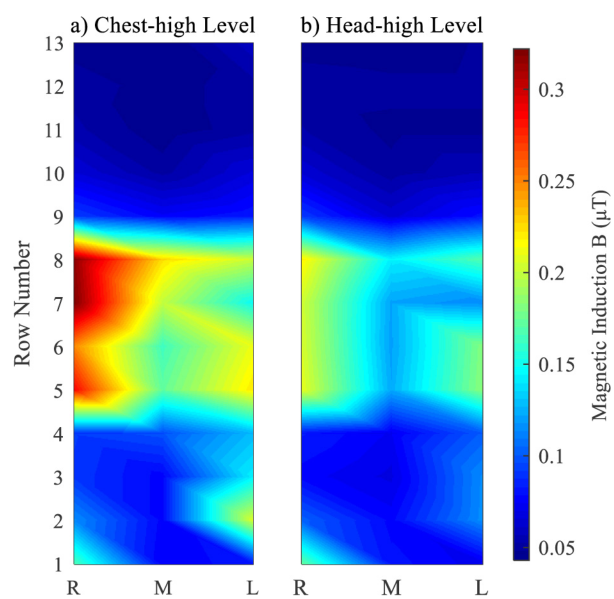

Figure 6. Magnetic induction distribution inside the bus

From Figure 7, we can notice that the tested magnetic induction level is much lower than general public exposure level from ICNIRP 2010, which means harmless to human body. The position closely above the ground is 19.23 μT. It is much higher than other test positions but still within the field limit. It should be noted that, the exposure level contains occupational exposure level and general public exposure level, of which the general public limit is more stringent. That is because the public contains people of different ages and physical qualities and they cannot realize they are exposed to EMF in most cases. For example, the field limits for the occupational and the general public are 100 μT and 27 μT. In conclusion, the ZXWPT030 system does not bring damage to public health, which makes it possible for introducing additional charging in daytime operation.

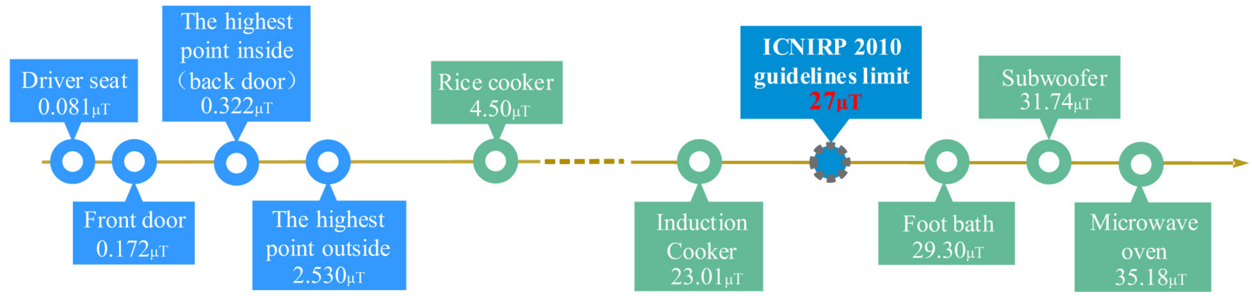

Figure 7. Typical Magnetic Induction Level

CHARGING PROCESS ANALYSIS AND MODELING

The charging characters are tested by ZLG PA2000mini Power Analyzer manufactured by Guangzhou Zhiyuan Electronics Co., Ltd. The phase current of the power grid are recorded separately with the help of three AC current clamps while the output current of PPC is measured by a DC current clamp. That is to say, the efficiency value calculated by power analyzer is the efficiency of the whole system, which contains the power loss between PrC and PuC as well as on all the components between battery and power grid. The output power of the system is limited to 40 kW. Charging process analysis is necessary to further evaluation of the whole operation cycle.

The charging power and the integral of charging power is shown in Figure 8. In the upper subfigure, we can notice that the charging power reaches its steady state in a multi-stage way. More than 0.4 kWh is accumulated during that period of time, which cannot be ignored. Thus, an equivalent-area method is proposed to simplify the whole charging process. At 23.5 s (the left gray dash line), the system gets started. After more than 65 seconds till 90.5 s, the output power becomes stable. This part can be calculated by integral of transient power, which refers to the area SI plus SIII. Assume that the output power of the system could instantly reach its steady state. Then the output power can be shown as the green dash line. In the same way, the output power during start-up process can be indicated by SII plus SIII, which encloses a rectangle area. The width of the rectangle is defined as Δt, while the height is the steady state power, P_{stead_state} = 37.15 kW. Thus, Δt can be calculated by Equation 1. Δt is calculated to be 44.8 s while t1 is 22.2 s.

$$\Delta t = {\left(S_{\mathrm{I}} + S_{\mathrm{III}}\right)} \Big/ {P_{\mathrm{steady\_state}}} \tag{1}$$

The efficiency of a plug-in electric bus is assumed to be 90% [14] while the wireless charging efficiency is assumed to be 85% [15 16]. The efficiency of the ZXWPT030 system can reach 87.89%, including the efficiency of REC (98%), PTC (99%) and PPC (99%). That is to say, the efficiency of power transfer between PrC and PuC gap can reach 91.50%. There still remains efficiency gap between plug-in charging and wireless power transfer. However, this gap is shrinking and even could be made up if we take its more flexible charging availability into consideration.

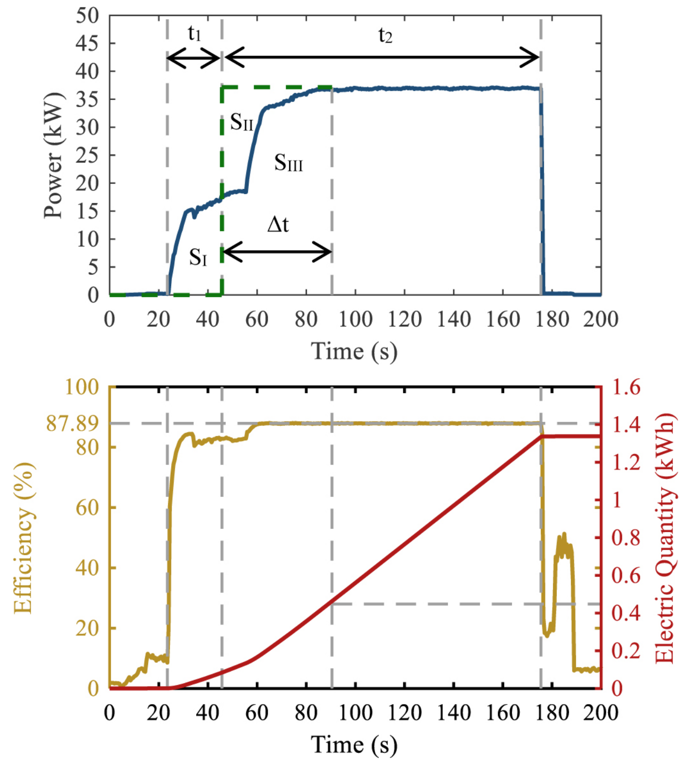

Figure 8. Electric Character of Wireless Charging Process

The power loss between PrC and PuC is due to the magnetic flux leakage and misalignment of PrC and PuC. For ZXWPT030 system, the system will be shut down automatically for misalignment protection when the secondary device is not centered well above PrC. Thus, a stable and high efficiency level can be ensured.

Figure 9 shows three examples of the tested system shutdown process. The sample interval of power analyzer is 0.5 s. It can be noticed that the shutdown processes do not follow the same rule. That is the distorting phenomenon which is caused by low sampling frequency. For the sampling time when the output power is descending, the former and the latter sampling time will always fall out of the descending process. Thus, it can be concluded that the whole shut down duration is less than 0.5 seconds. This period of time is too short compared with the operation duration, which is negligible and can be ignored in charging process modeling.

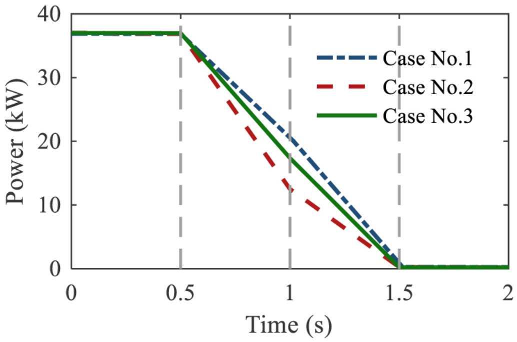

Figure 9. System Shut-down Process

In conclusion, the whole charging process can be divided into two parts, t1 and t2. During t1, no power is available while at t2, the output power is considered to step to its steady state. Besides, t1 is caused by the system inherent characteristics and cannot be avoided. This part is combined with the period of time spent for alignment, which will be mentioned below. Therefore, the charging model can be simplified as a ramp function, whose slope is the steady state output power.

DAYTIME OPERATION

Introduction of Commercial Demonstration Bus Line

The commercial demonstration bus line is shown in Figure 10, which is recorded by V-990 multifunction GPS data logger. The No. 306 bus line is 43.6 kilometers long. There are four diesel engine powered buses and four wireless charging electric buses (the buses are numbered as BA001, BA002, BA003 and BA004) to fulfill the operation task each day from 6:30 am in the morning to 7:30 pm in the evening. As scheduled, the diesel fueled bus and electric depart from the starting station alternatively. The departure interval will be shortened during morning and evening peak while be lengthened in the afternoon and after evening peak.

Figure 10. Commercial Demonstration Bus Line

Just like plug-in electric buses, the wireless charging buses are designed to charge over the night and operate as a pure electric bus in the day. The buses will not get charged in the day. If one's SOC is too low to cover its next roundtrip, its operation task will be taken over by diesel engine powered buses. Thus, each bus is equipped with a large-capacity battery. With the battery capacity attenuation, more electric buses have to drop out from operation in advance. Our team is assembled to evaluate the potential of this commercialized wireless charging system and propose a more efficient operation strategy.

Operation Analysis and Modeling

For a commercial bus line, the operation process should be guaranteed with the highest priority. To further investigate on this issue, the operation model is the key part of the whole operation cycle model. During the on-board test, driving time, mileage SOC (state of charge) and the GPS data are recorded. Three drivers volunteered to participate into our tests. In order to better demonstrate the relationship between SOC and time or mileage, the minimal element in each SOC data vector is chosen as the basic value and other elements are replaced by the difference between their original value and the basic value. Thus, the initial SOC refers to the consumed SOC to cover a single roundtrip.

Figure 11 shows the relationship between SOC and driving time. Linear regression method is adapted. The fitted linear parametric equation is shown as Equation 2, of which the slope is -0.003 SOC/s. Besides, SOC will descend by 19.3976% each time after one roundtrip. The variance of Δ SOC is 0.8906 and the correlation coefficient of training data and the fitted linear parametric equation is 0.9884.

$$y = -0.003x + 19.3976 \tag{2}$$

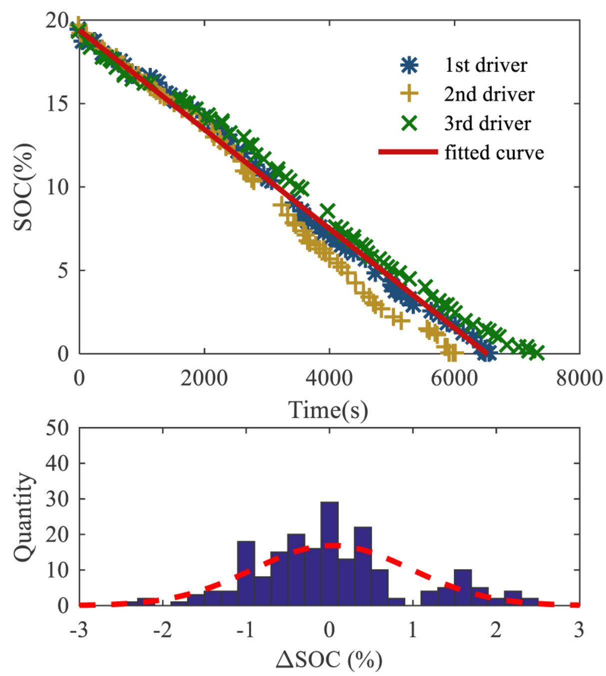

Figure 11. SOC Change Along with Time

Figure 12 shows the SOC change along with mileage. Linear regression method is adapted to build this model. The fitted linear parametric equation is shown as Equation 3, of which the slope is -0.449 SOC/km. Besides, SOC will descend by 19.1287% after one round trip. The variance of Δ SOC is 0.1233, which is lower than that in the SOC-time case. That is because roundtrip duration depends on drivers' driving styles. Drivers with different driving styles will result in different roundtrip cycle. The correlation coefficient of training data and the fitted linear parametric equation is 0.9981, which shows good linear relationship between SOC and mileage.

$$y = -0.449x + 19.1287 \tag{3}$$

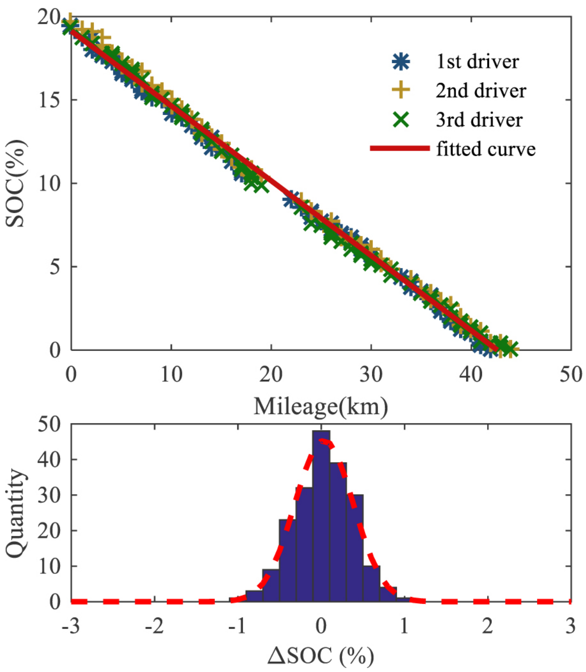

Figure 12. SOC Change Along with Mileage

In conclusion, the length of a specific bus line is fixed while the roundtrip duration varies with different drivers because of their different driving styles. Moreover, higher correlation coefficient indicates a stronger linear relationship between SOC and mileage. The correlation coefficient is 0.9981, which shows strong linear relationship between SOC and mileage. Therefore, the linear relationship between SOC and mileage can be used to build a simplified operation modeling. The complex vehicle dynamical model and bus route operating model can be saved.

OPERATION CYCLE QUANTIFICATION AND MODELING

The following flow chart shown in Figure 13 explicitly describes the entire working process in the bus parking lot. Buses are strictly scheduled for operation at certain time points during the day, which starts from early in the morning till night. Eight buses take turns to depart from the starting station. Due to the short distance from the parking lot to the starting station, it usually takes two minute or little more for a bus to arrive. Then, it starts to operate in the 43.6-kilometer-long route, which is called a roundtrip. After the bus return to the starting station, which now should be referred to as the terminal, the bus would head for the parking lot to check in. As for the four electric buses, their arrival sometimes means the imminent need for recharging, depending on its SOC. There are two pads available for wireless charging.

The entire operation process can be quantified as following:

a. The staff in duty will check the planned schedule for departure as well as buses available. When it comes to a departure time point, the available bus will start driving for the starting station, which takes 1’30” to 1’40” according to statistics. This time is defined as T_3, quantified as 2’00”.
b. The bus will then begin its operation. According to our statistics, it takes 105’00” in average to cover the route from the starting station to the terminal. This time is defined as TRUN, equals 105’00”.
c. After arriving at the terminal station, the bus driver faces a choice to park the bus in the parking lot waiting for next departure or recharge the bus on the charging pad. This choice is made in consideration of two factors: first of which is the SOC; the second is the scheduled departure time.
   i. If there remains enough electricity to launch another departure, then the bus will be driven to the parking lot, which takes roughly the time equals to T_3. And this period of time is defined as T_1, equals to 2’00”. After that, the bus will waits till its next departure.
   ii. If the bus driver finds the bus is in need of charging, he would drive the bus to the charging pad first.
d. It usually takes less than one minute for a driver to drive the bus from the terminal station to the charging pads. This time is defined as T_2, which equals to one minute.

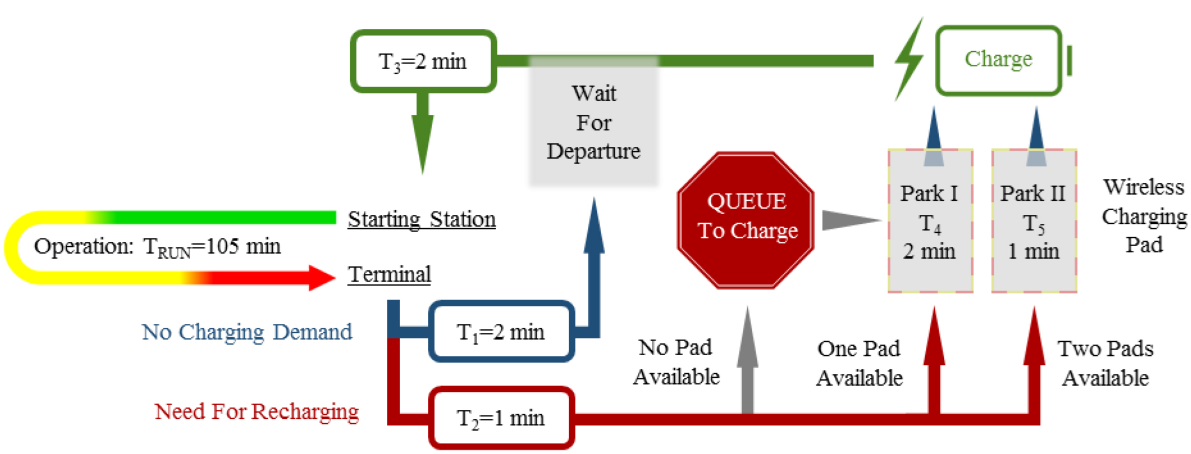

Figure 13. Operation Cycle Quantification

e. The next step is for the driver to park the bus on the charging pad.
   i. If neither the two pads are occupied, the driver can enjoy a relative broad area to park. Although it demands precise alignment to park the bus in the specified place, the bus drivers have shocked us by their marvelous skill of parking. In most cases, it takes a driver less than thirty seconds, and some can even park the bus right into the position in five seconds. The statistics shows that the average parking time is about 25s. However, due to one certain reason, we expend and define this time as one minute, which will be explained in detail. So this time is symbolized as T_5, equals to 1’00’’.
   ii. If one of the two pads is occupied, it will cause some trouble for the driver to park due to the cramped path made by the other charging bus. The statistics shows that the average time to park is roughly 1’20’’. But we expand this time as two minute as well for the same reason. It is defined as T_4, equals to 2’00’’.
   iii. If both pads are occupied, the driver has to park the bus nearby until one of the charging buses leaves.

f. After the bus has been well positioned, the system will get charged immediately. As the preceding text has discussed, the charging power stabilizes in about 70 seconds after initiation. And for convenience, we assumed that before the first 21.3’’, the charging power is zero. After that, the charging power steps to the stabilized power. This method can simplified the charging model while ensuring the electricity quantity being charged during this period unchanged. This is the reason we add a redundant time into the T_4 and T_5.

g. The bus will quit charging under three circumstances. The first is that the battery has been fully charged. The second is that the SOC has reached an assigned point, and the scheduled required the bus for departure. The third is that the SOC has reached the assigned point as well as another bus is waiting for charging.

h. The bus which quits charging will be immediately parked in the parking lot waiting for its next departure. Then, we come back to the origin.

In conclusion, the whole operation cycle can be specified as nine modes, which are defined in Table 4.

Table 4. Definition of Mode

Mode	Definition
1	Waiting for departure
2	Time spent on way to the starting station
3	The operation
4	Time spent on way to another departure
5	Time spent on way to charging
6	Parking when one charging pad is occupied
7	Parking when both charging pad are available
8	Waiting to charge
9	Charging

In these nine modes, six of them can be determined in advance. As shown in Table 5. The rest three modes do not have a fixed time, for its durance depending on other factors.

Table 5. Definition of Time

Symbol	Time	Definition
T_1	2’00’’	Time spent on way to another departure
T_2	1’00’’	Time spent on way to charging
T_3	2’00’’	Time spent on way to the starting station
T_4	2’00’’	Parking when one charging pad is occupied
T_5	1’00’’	Parking when both charging pad are available
T_{RUN}	105’00’’	Time spent on one operation

RESULTS AND DISCUSSIONS

The bus line 306 in Changsha have a departure schedule for 36 operations one day, starting from the first roundtrip at 6:30 am to the last one in 7:30 pm. Line 306 owns 8 buses, four of them are electric buses while the rest are diesel engine powered buses. The four electric buses carry out 18 operations a day, and get charged mainly during the night. That is to say, the electric buses are designed to operate in the day without charging. Hence the batteries should cover at least five roundtrips. However, in the actual commercial operation, bus drivers find that battery capacity becomes insufficient with the battery capacity attenuation. Thus, extra charging process should be introduced. Our team established an operation cycle model to analyze the daytime electricity consumption, along with its maximum electricity quantity usage. Such comparison between different ideas can show how much battery capacity is enough to support the operation.

Plug-in Electric Bus

Plug-in electric buses are designed not to recharge during the day. This condition requires the buses to be able to sustain the operations of the entire day without any energy refill. The plug-in case follows the restrictions below:

i. The electric buses and the diesel buses are launched for operation successively, one by one after each other.
ii. The battery capacity on one bus should be bigger than the minimum amount that is able to satisfy the requirement of running all day without charging.
iii. The daily operations carried out by electric buses must live up to eighteen times as required.

The electricity consumption of plug-in buses during day time operation is shown in Figure 14.

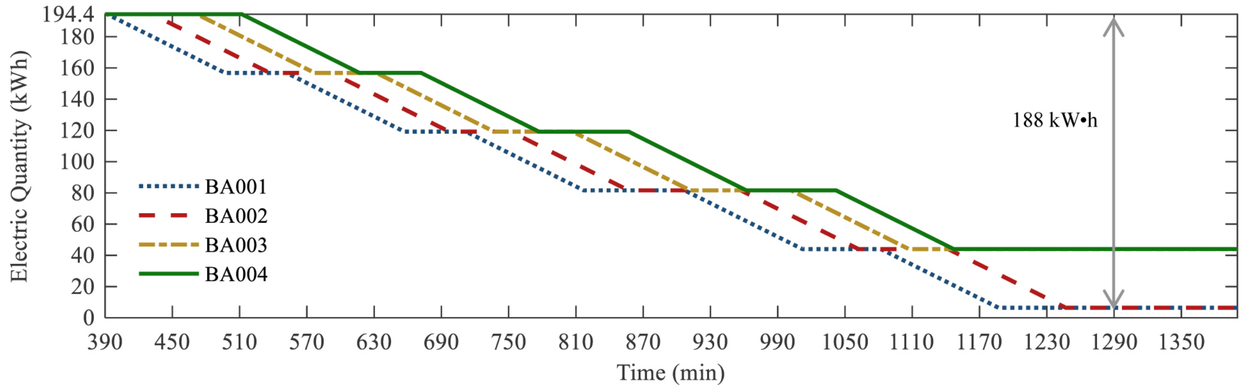

Figure 14. Electricity Consumption of Plug-in Buses during Daytime Operation

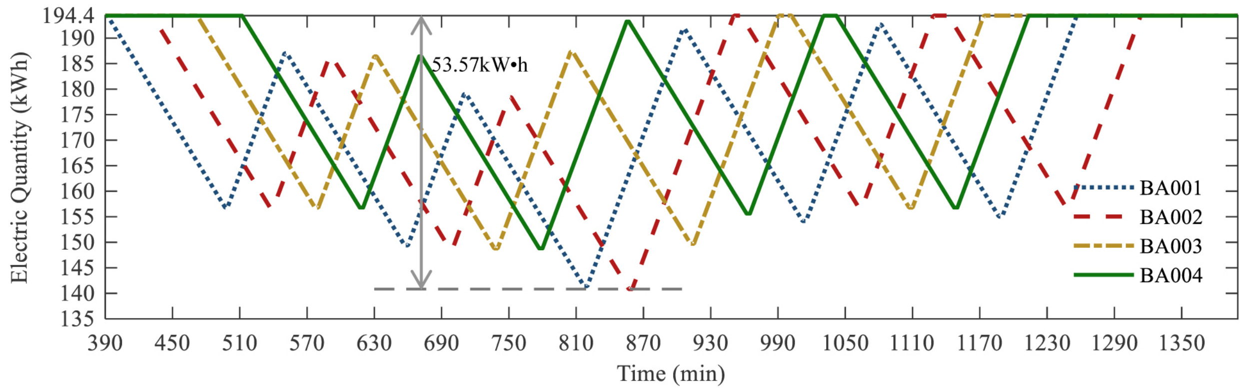

Figure 15. Electricity Consumption of Wireless Charging Buses with Fixed Departure Schedule

Under such requirements, we assigned 18 interval time on the departure schedule to electric buses. The result shows that two electric buses operate four times respectively, while the other two buses operate five times. From the simulation results we can notice that the minimal electricity quantity which can support this case is 188 kW•h, which is close to the current battery capacity of wireless charging electric buses. In other words, the buses can cover daily operation duty only if the electric buses' batteries can function normally. However, the battery capacity of two buses will be nearly depleted by the end of the daily operation. It will have a negative influence on battery lifetime for battery over discharge. Thus, this operation strategy without daytime charging is harmful to battery lifetime and not recommended.

Wireless Charging Electric Bus with Fixed Schedule

Wireless charging electric buses are equipped with wireless charging coils which allow them to have better mobility as the charging pads can be easily set in any parking lot. In this case, we firstly simulate the situation where there still remains similarities with the actual operating pattern in Line 306.

Current protocols of Line 306 illustrate that electric buses and diesel buses should depart successively with each other. So in this case, electric buses have a fixed schedule just the same as the one in plug-in case. The wireless charging electric buses with fixed schedule case follows the restrictions the same as the ones in the case above.

i. The electric buses and the diesel buses are set out for operation successively, one by one after each other.
ii. The battery capacity on one bus should be bigger than the minimum amount that is able to satisfy the requirement of running all day without charging.
iii. The daily operations carried out by electric buses must live up to eighteen times as required.
iv. Whether to recharge or not should depends not only on battery SOC but also on the availability of the charging pad and charging demand of other buses.

The electricity consumption of wireless charging buses with fixed departure schedule is shown in Figure 15. From Figure 15, it is easy to recognize which bus has the maximal electricity consumption.

In this case, the departure time of the electric bus are still scheduled. Electric bus and diesel fueled buses depart on by one and finally covers all the 36 roundtrips. The only difference from the plug-in case is that the charging opportunity is available only if the charging lot is not occupied. Then, the battery can get charged in daytime. Thus, more battery size can be saved. The extra charging opportunities can make the buses fulfill its operation tasks with only 53.57 kW•h, which is much less than the one in the plug-in case. This operation strategy requires drivers to recharge the bus every time they finish their operation until the bus is ready for its next operation. For a bus utilizing wireless charging technology, the bus can get charged automatically, which will not bring any burden to the driver.

This conclusion affirmatively confirmed that recharging during daytime is highly beneficial. In the meantime, it reveals the great potential on battery reduction simply following an improved version of the current operating pattern that Line 306 follows.

Wireless Charging Electric Bus with Free Schedule

The conclusion in the wireless charging electric buses with fixed schedule case arouse our further interest in researching possible solutions for a smaller electricity quantity usage. This time, electric buses are no longer required to be launched every time after a diesel bus. For the mature and stable performance of diesel buses is well recognized, we have enough confidence to give electric buses a free schedule, which means that electric buses have priority to diesel buses when it comes to decide which bus should go in a scheduled departure time point. However, such conditions may cause no electric bus is available to set off for a few departure time points in succession, which may further results in four diesel buses cannot maintain the circulation. To prevent such scene from happening, the wireless charging electric buses with free schedule case should follow the restrictions below:

i. The electric buses and the diesel buses are not set out for operation successively, one by one after each other.
ii. The battery capacity on one bus should be bigger than the minimum amount that is able to satisfy the requirement of running all day without charging.
iii. The daily operations carried out by electric buses must live up to eighteen times as required.
iv. The criteria of whether to recharge or not should be plain and operable for drivers
v. It is not allowed to have five successive scheduled departure time for any certain type of buses.

Figure 16 and Figure 17 shows real time power consumption and operation mode of individual bus during daytime operation. Totally 10 roundtrips are completed by BA001 and BA002 while BA003 and BA004 each complete 4 roundtrips. The other 18 roundtrips are completed by diesel fueled buses. The real-time mode can indicate where the bus is and what state is the bus right now. In a word, the mode of a bus results from comprehensive factors, which not only depends on the departure schedule, but also on the priority between its current demands and that of other buses. The algorithm can calculate the minimal battery capacity the buses need to cover the daily operation tasks, which ensure the battery downsizing potential have been adequately explored.

In this case, the diesel engine powered bus and electric bus are not scheduled to depart alternatively. Simulations results show that, a flexible schedule can further reduce the battery size. As shown in Figure 18, a bus can complete its operation task with a battery size of 41.44 kW•h. The stipulation for drivers is similar with the one in the fixed-schedule case, where the drivers are requested to recharge the bus every time they finish their operation until the bus is ready for its next departure. This amount of electricity quantity is close to the electrical power consumed in one operation, showing a further potential for battery reduction.

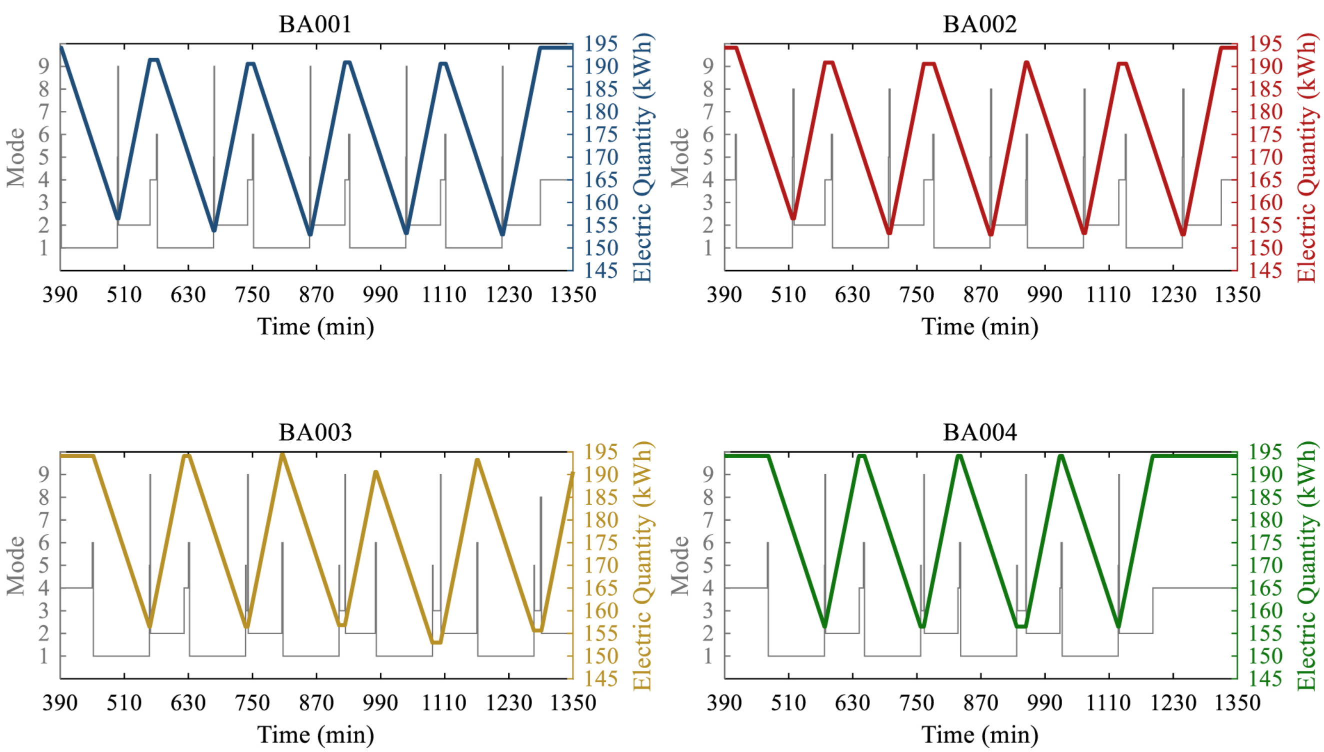

Figure 16. Power Consumption and Operation Mode during Daytime Operation

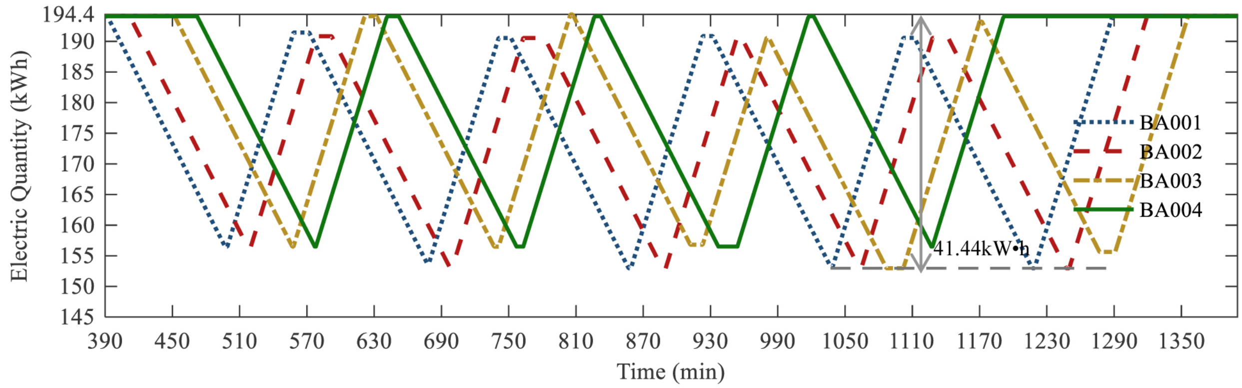

Figure 17. Electricity Consumption of Wireless Charging Buses with Free Departure Schedule

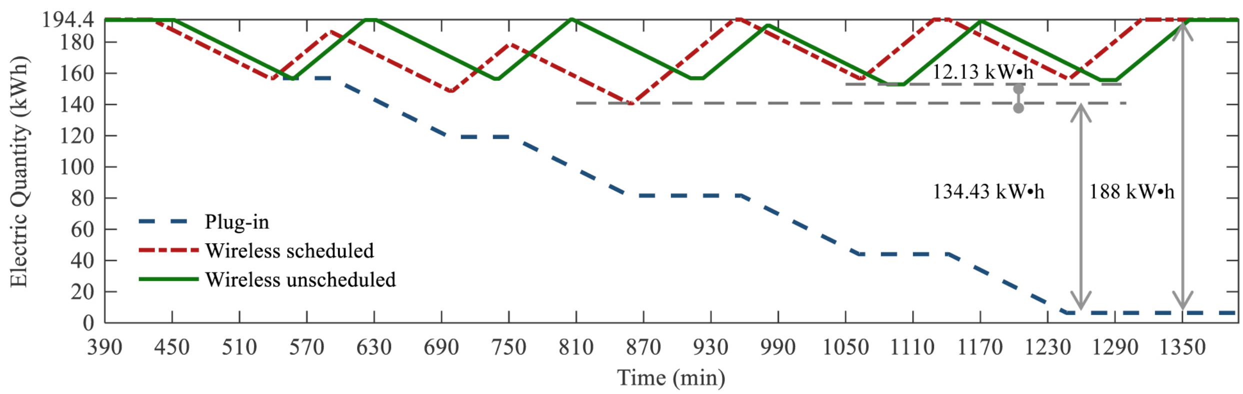

Figure 18. Comparison between the Maximal Power Consumption Buses of Each Case

Figure 18 compares the buses which consumes the maximal power in each case. In summary, the battery size can be reduced by 134.43 kW•h if wireless charging technology is adapted. Furthermore, the battery size can be further reduced by 12.13 kW•h if the departure schedule is not fixed. Thus, totally 146.56 kW•h battery size can be saved, which means more than 70 percent of the battery size can be saved. Besides, the current battery size can cover the operation tasks without extra charging opportunities. However, the battery size is still recommended to be larger because of over discharge protection.

The battery size of a plug-in charged battery can be divided into four regions: overcharge safety margin, operating region, reserved storage capacity and no operation region [17]. Among them, operation region indicates the minimal battery energy requirement for an electric bus to fulfill its daily operation tasks. Thus, the battery size mentioned above refers to the operation region. To get the total battery size, other three parts should be taken in to consideration for over charge protection, over discharge protection and reservation for battery capacity attenuation.

The battery downsizing potential is restricted by SOC descending slope along with mileage. The removed battery weight can reduce the rolling resistance of vehicle, which brings greater potential for battery downsizing. For a sedan, 10% vehicle mass reduction results in a possibility of 4~7% energy reduction for electric vehicles [18] while EVs are less sensitive to mass-induced energy consumption reduction because of braking energy regeneration [19].To push the research to the next step, a vehicle dynamical model is necessary to evaluate how much contribution the removed battery weight can make to energy consumption reduction.

CONCLUSIONS

This paper conducts investigation on a commercial demonstration bus line utilizing wireless power transfer technology. In this paper, the operating cycle is quantified and modelled, of which the charging and running process are simplified and modeled based on experimental data. Currently, the buses are designed to operate in the day and get charged at night. In order to explore the battery downsizing potential, plug-in electric bus line, wireless charging bus line with fixed and free departure schedule are simulated and compared.

The magnetic exposure level of the wireless charging system is tested according to the International standard IEC-TC69-PT61980. Results show that the magnetic induction level is within the general public exposure limit from ICNIRP Guidelines 2010, which means harmless to human body and makes it possible for extra day time charging opportunities.

Charging and operation hours are necessary parts of daily operation. The charging power is simplified as a step function through "equivalent area" method, which takes the electric energy consumption during stair-like starting process into consideration. During operation hours, SOC descends almost linearly by time and mileage. Results show that the linearly fitted curve of SOC and mileage has a higher correlation coefficient than that of SOC and operation time. That is because for a dedicated bus line, the mileage is fixed while the roundtrip duration depends greatly on the drivers' driving style.

The operation duty cycle is quantified and modeled. With the help of this model, electric energy consumption under different charging strategies are simulated and compared with each other. Results show that the battery size can be reduced by 134.43 kW•h if wireless charging technology is adapted. The battery size can be further reduced by 12.13 kW•h if the departure schedule is free. Thus, totally 146.56 kW•h battery size can be saved, which means more than 70 percent of the battery size can be reduced.

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DEFINITIONS/ABBREVIATIONS

SOC - State of charge

GPS - Global position system

BMS - Battery management system

EV - Electric vehicle

WPT - Wireless power transfer

PrC - Primary coil

PuC - Pick-up coil

REC - rectifier

AC - Alternating current

DC - Direct current

PTC - Power transmit control

PPC - Power pick-up control

IVU - In vehicle unit

RFID - Radio frequency identification device

CSU - Communication service unit

AP - Access point

PMSM - Permanent magnet synchronous motor

EMF - Electromagnetic field

IEC - International electro-technical commission