Energies **2015**, *8*, 6806-6819; doi:10.3390/en8076806

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

An Electric Bus with a Battery Exchange System

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Academic Editor: Joeri Van Mierlo

Received: 7 May 2015 / Accepted: 30 June 2015 / Published: 7 July 2015

Abstract: As part of the ongoing effort to be independent of petroleum resources and to be free from pollutant emission issues, various electric vehicles have been developed and tested through their integration with real world systems. In the current paper, yet another application specific EV for public transportation, an electric bus, is introduced and explained with results from the pilot test program which was carried out under real traffic conditions. The main feature of the current system is a battery exchanging mechanism mounted on the roof of the bus. The current configuration certainly requires an externally fabricated battery exchanging robot system that would complement the electric bus for a fully automated battery exchanging process. The major advantage of the current system is the quick re-charging of the electric energy through the physical battery exchange and the possible utilization of the battery exchange station as a mini scale energy storage system for grid system peak power shaving. With the total system solution approach for the public transportation system, it is fully expected to create outstanding business opportunities in number of areas such as battery suppliers, battery exchanging station management, battery leasing and many more.

Keywords: electric bus; public transportation; battery exchange; energy storage system

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1. Introduction

Greenhouse gases such as CO_2 are known to be a major cause of global climate change along with unexpected and unprecedented local weather changes [1–3]. Regulatory efforts to minimize the production of CO_2 have been made in many countries and so far, have served their purpose to some degree. However, CO_2, as are we all aware, is a product of the combustion process of an IC engine so long as the engine uses HC-based fuels. In short, the most effective way to lower the overall production of CO_2 is to not use IC engines that run on HC-based fuels. Also, in the recent reports regarding the CO_2 production in the U.S. [4] and in Korea [5], about 28% of the overall CO_2 production in the U.S. and about 20% of the overall CO_2 production in Korea were from a transportation sector. With this significant CO_2 production in the transportation sector, abundant research has been conducted to provide various solutions to society, including hybrid electric vehicles, fuel cell vehicles, and plug-in hybrid electric vehicles, as well as pure electric vehicles, and many of them have been actually introduced to the public as mass produced products. From the experiences over the last few decades, it has been realized that no single silver bullet solution exists, mainly due to the dynamic nature of consumer expectations for different types of vehicles.

Many studies about the future of society have shown a number of key future megatrends [6]. One of them was reported to be urbanization, in other words, a growth of city life with high density populations and high rise buildings. As a natural result of this trend, it is fully anticipated that the traffic congestion and the pollutant emission problems will become prominent. While various types of vehicles using alternative fuels, including hydrogen-based electric fuel cell powertrains [7], have been researched to mitigate pollutant emissions, including greenhouse gases, most of them were developed rather independently without really considering the effects on the city-wide transportation system. For that reason, many traffic analysts have reported the importance of city-wide public transportation systems including buses [8], trams, subways and even bimodal extended or double deck buses as well.

As a background for the current research, the representative characteristics of the inner-city commuter bus can be summarized as follows: firstly, bus services run on predefined routes with predefined time schedules. Secondly, bus services run continuously during the service hours. In other words, the bus will not stop and rest at the main terminal for a long time unless it is out of service. This is to maximize the bus fleet usage without parking at the garage. These characteristics have both positive and negative implications for the electrification of buses. On the positive side, electric buses can be optimized to fully satisfy the predefined routes and schedules to a certain degree. On the negative side, electric buses have to find a way to recharge their batteries very quickly to avoid any delay at the terminal [9,10].

In Korea, buses typically stay at the terminal for about 30 min or less to refuel and rest and then, head out for the next service with a new driver. Otherwise, the bus service company has to stock extra vehicles to fill the gap between the refueling and rest time. In order to satisfy the requirements for the inner-city commuter bus with an electric bus, it has to be optimized for the service routes and schedules as well as a quick and efficient recharging mechanism to avoid any extended refueling delays at the terminal [11]. With these constraints in mind, a careful study concerning the optimal placement of battery exchange stations was performed [12] and a comparison between and optimal planning of battery quick charging and a battery swapping strategy was further carried out and reported [13–15]. In these papers, the advantage of a battery exchange strategy over the quick charging strategy for the case of public transportation system was well explained through their in-depth analysis. Also, more studies on energy buffers and storage systems for bus powertrains were conducted [16,17] and ideas about DC quick charging stations and ultrafast EV charging stations to support public transportation systems were examined and reported [18,19].

In this paper, an electric bus built with a roof-top mounted battery exchanging mechanism is introduced and the field test results from a pilot program are also explained do demonstrate its suitability as a public transit solution. With minimal time required for the automatic battery exchange process (less than a minute), its usefulness as an inner city transit service has been maximized. With the increasing importance of public transit systems as more and more mega cities are appearing, the current battery exchanging electric bus is fully anticipated to contribute to the reduction of traffic congestion problems as well as to the reduction of CO_2 emission issues.

2. Public Transportation Solution with an Electric Bus Integrated with a Roof-Top Mounted Battery Exchange System

The electrified inner-city commuter bus solution consists of three major systems, namely, an electric bus with the roof-top mounted battery exchange mechanism, a battery exchange robot and storage station and an exchangeable battery pack solution.

The battery exchange robot and storage station are established at certain locations along the bus service route. An electric bus equipped with the battery exchange mechanism runs the designated routes. When the electric energy of the battery on the bus is depleted and it needs to be replaced with the fully charged one, the electric bus will be notified to visit the battery exchange station to get a fully charged battery. The discharged battery from the electric bus will be recharged at the battery exchange station using a carefully scheduled battery charging policy to avoid possible overloading of the existing power grid system in the city. With this integrated approach, the electric buses with the battery exchange system can be optimized for specific bus routes, and the proper locations of battery exchange stations can be optimized to ensure smooth service operation.

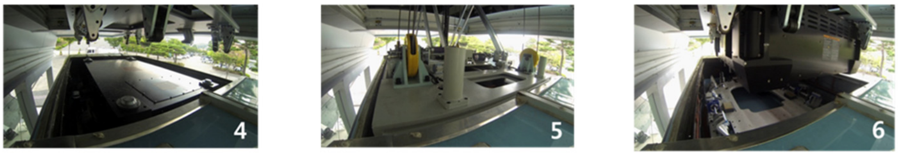
In the current research, the bus routes in Seoul, Korea were taken into consideration. The average round trip distance of the bus routes in Seoul is about 35.3 km [20]. A preliminary analysis by urban traffic experts suggested establishing the battery exchange stations every 20 km based on a study of the return on investment [21]. The battery sizing and powertrain were optimized to run for this target distance with passengers while operating an appropriate HVAC system, depending on the weather conditions.

As illustrated in Figure 1, the overall sequence of the battery exchange process is fully automated. Currently, the time interval for the battery exchange process is about 60 s, which satisfies the target considering the time required for passengers to get on and off the bus.

Approaching the battery exchange station

Opening the door of battery exchange station

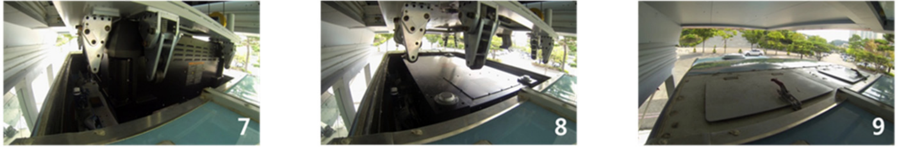
Opening the roof door of the electric bus



Positioning the battery extracting robot arm

Grabbing the battery mounted on the roof of the electric bus

Extracting the discharged battery from the electric bus



Inserting the fully charged battery

Releasing the battery on the roof of the electric bus

Closing the roof doors of the electric bus and the battery exchange station

Figure 1. Illustration of the battery exchange process.

3. System Integration of Electric Bus with a Battery Exchange System

The electric bus was designed to meet the requirements from the overall solution for the currently proposed transportation system. Autonomie, a commonly used design tool for the energy balancing and management of vehicles, originally developed by the Argonne National Lab (ANL) in the U.S., was used to estimate the sizes of powertrain components, energy storage device and other accessory systems such as a heater and air conditioner as well as auxiliary motor to drive legacy components that require vacuum and compressed air. As shown in Figure 2, the overall architecture includes dual traction motors with a combined gear box and two auxiliary motors for the operation of accessories. A 70 kW braking resistor is installed to support the heater requirements of the bus during winter operation and a mechanically driven A/C is included to provide proper cooling of the bus during summer operation.

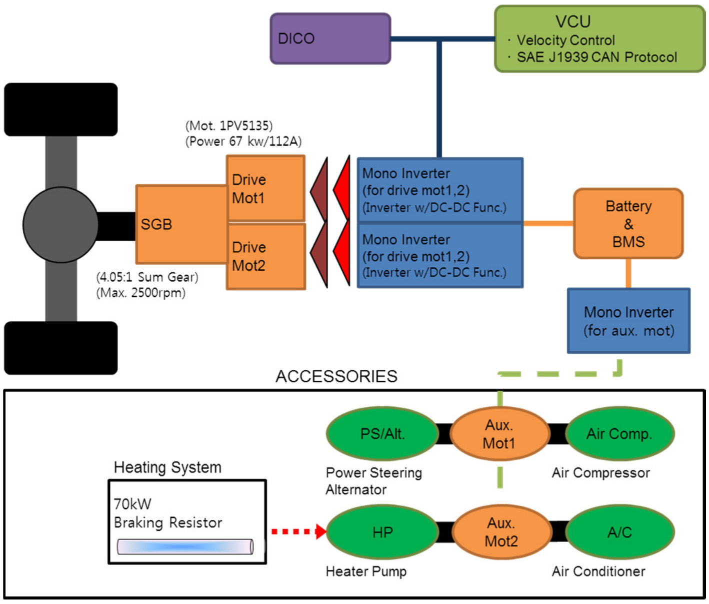


Figure 2. Overall architecture of electric bus.

In Figure 3, the energy model of the target vehicle specifications is illustrated. An initial model was developed and various vehicle performance features were estimated including driving range, energy consumption, acceleration, climbing angle and more. For the initial design cycle, only the standardized driving cycle, namely a Manhattan bus cycle, was used. After the completion of the first vehicle prototype, this energy simulation model was validated with experimental data. In particular, the locally obtained driving cycle where the first field test were planned in the real world environment, was heavily used to fine tune the vehicle configuration. The validated vehicle energy model from this initial prototype and the target driving cycle was extensively used to design the next few prototypes to more precisely meet the needs of the overall transportation system strategy.

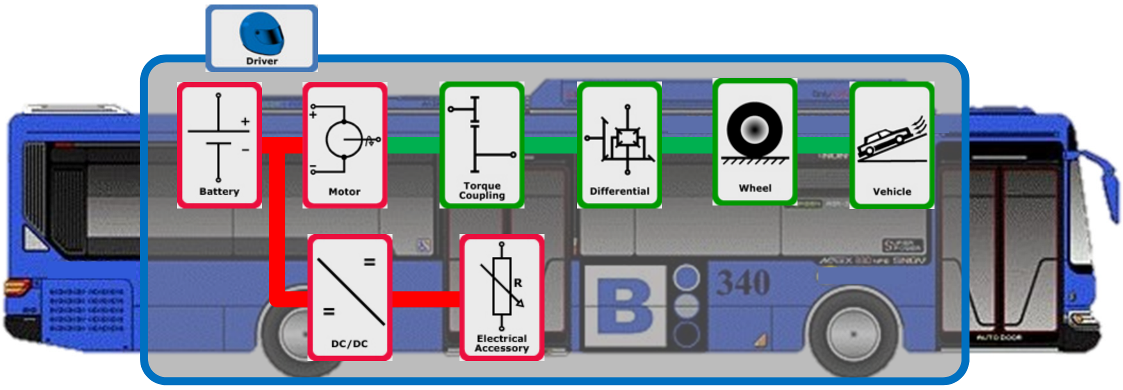


Figure 3. Energy model built with Autonomie from ANL.

A unique feature of the electric bus with the roof-top mounted battery exchange system is the battery mount shown in Figures 4 and 5. The roof door is a sliding type and it opens the access area for the easy battery exchange. This mount guarantees the alignment of the battery pack from the battery exchange robot and provides a strong holding mechanism for the exchangeable battery packs. The sliding door mechanism is carefully designed to effectively block rain or snow and at the same time, if there are any leaks along the rim of the door contacts, the geometry of the railing mechanism is designed to guide the rain to water drain holes to protect the battery in such a case.

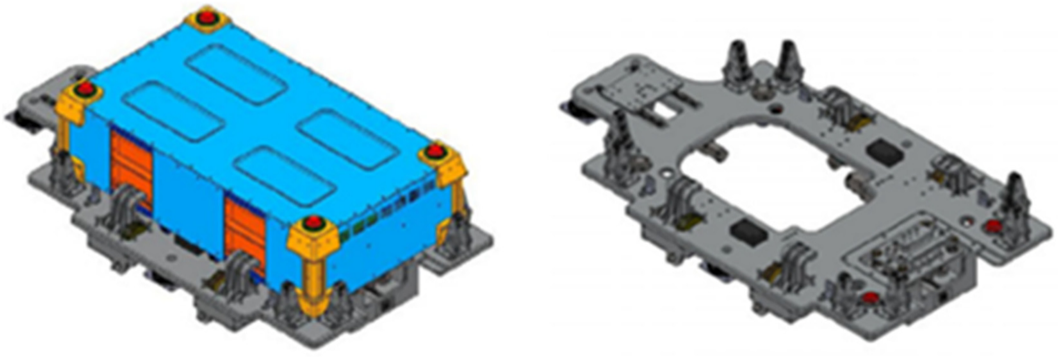


Figure 4. Battery mount shown with and without the battery.

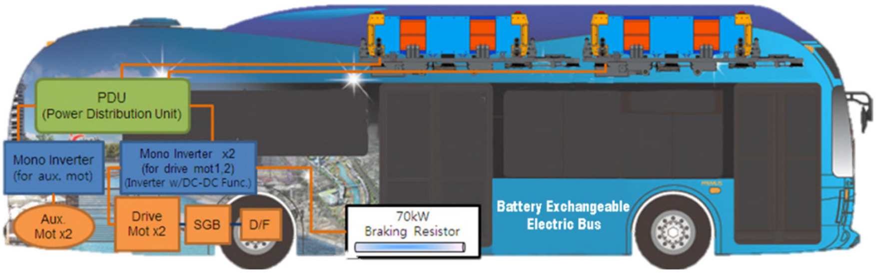


Figure 5. Roof top mount battery exchange system.

As shown in the schematic diagram (Figure 2), the following electric powertrain components and the energy storage systems were integrated along with the communication system, vehicle control unit and instrument panel.

1. Two 120 kW traction motor units were connected directly to the combined gear box in parallel in order to mechanically combine the torque from the two motors. The output shaft from the gear box was connected to the final differential gear box for further reduction of RPM while boosting the torque to the wheels.
2. Two 20 kW auxiliary motor units were connected in parallel and they are mainly used to drive the power steering pump, air compressor, A/C compressor, heater pump, alternator, braking resistor and miscellaneous accessory devices.
3. Driver controllers are used to control the inverters for the main traction motors and auxiliary motors, respectively.
4. A supervisory controller for the vehicle known as a vehicle control unit (VCU) is used to harmonize vehicle subsystems through a CAN-based communication protocol just like the one found in many other vehicle systems.
5. Li-polymer type battery cells are used to make a swappable battery pack with 48.62 kWh of energy capacity. The main swappable battery pack is installed right under the roof door and optionally, a second battery pack can be installed under the roof door as a range extender or as an emergency backup battery.
6. The swappable battery and the backup battery can be used alternately and can be selected with an externally controlled switch either by manual or automatic operation.
7. The batteries can also be recharged through the charging inlet connector separately prepared at the side of the bus using a slow charger while they can usually be recharged at the battery exchange station.
8. A newly developed instrument panel is used to display the state of charge of the battery, voltage level of the battery, temperature of the battery, temperature of the traction motor, power consumption by the motor, vehicle speed, warning and error messages and even the usage time of the motor.

3.1. Electric Bus

The electric bus was converted from an existing model from a bus manufacturer. While keeping the original body frame as originally designed, various modifications were made to the bus, including suspension system changes to handle the load from the additional weight imposed by the conversion.

After the conversion was completed, an official examination of the converted electric vehicle to obtain the vehicle operation certificate was carried by the appropriate government authority for its safe operation on public roads. A brief list of the bus specifications is provided in Table 1.

Table 1. Specifications of the base model.

Dimensions		11,055 × 2485 × 3490 mm			
Number of passengers		50			
Tires	Front	11R22.5–16PR(S)			
	Rear	11R22.5–16PR(D)			
Suspension type	Front/Rear axle	Rigid axle suspension (dependent type suspension)			
Curb weight	Front axle	4490 kg	Gross weight	Front axle	5880 kg
	Rear axle	7060 kg		Rear axle	8855 kg
	Total	11,550 kg		Total	14,735 kg

3.2. Electric Powertrain

The electric powertrain was selected based on the initial vehicle energy analysis with the Autonomie simulation tool. Since the main purpose of the current research is not to develop a new electric powertrain, but rather to integrate a new transportation solution, a commercially available electric powertrain was adopted for its stable and durable operation. Specifications of the current electric powertrain components used in the solution are provided in Table 2.

Table 2. Specifications of the electric powertrain.

	Type	**AC Induction**
Drive Motor	Rated Voltage	650 V
	Continuous Power	67 kW
	Peak Power	120 kW
	Max. Torque	430 Nm (300 A)
	Max. Speed	10,000 rpm
Auxiliary Motor	Type	AC Induction
	Rated Voltage	450~650 V
	Continuous Power	16 kW
	Peak Power	20 kW
	Max. Torque	120 Nm (90 A)
	Max. Speed	5000 rpm
Inverter	Operating Voltage	300~750 V
	Rated Current	250 A
	Max. Current	350 A (10 s)

3.3. Battery Pack

Li-polymer cells (162 cells in series and 4 strings in parallel) are used in the battery pack, connected to provide an operating voltage of 607.5 V with 80 Ah, and total energy storage capacity of 48.62 kWh. Detailed specifications of the battery pack are listed in Table 3.

Table 3. Specification of battery pack.

Type	Li-Polymer
Connection Type	162S4P
Nominal Voltage	607.5 V
Capacity	48.62 kWh
Max. Discharging Current	400 A
Cont. Discharging Current	160 A
Max. Charging Current	160 A
Operating Temperature	−20–60 °C

4. Performance Evaluation

4.1. HVAC Energy Requirement

4.1.1. Test Configurations

In order to roughly measure the requirements for the heating, ventilating and air conditioning, the energy consumption of the electric bus was closely monitored and evaluated in a closed test track provided by KATRI and shown in Figure 6.

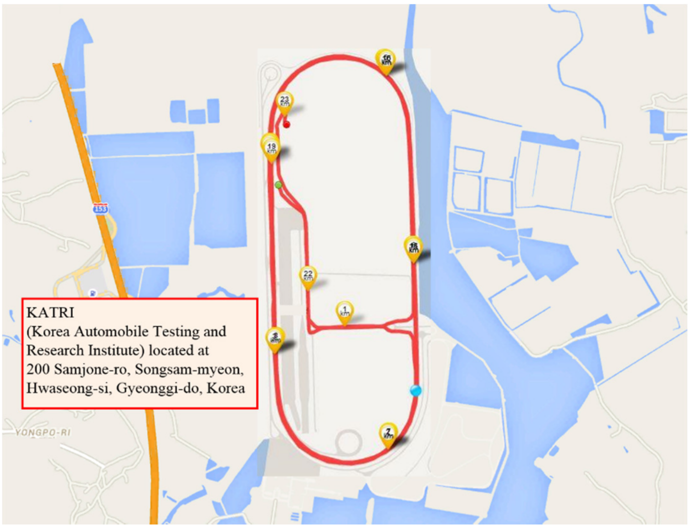


Figure 6. Test track for HVAC system test.

The HVAC system was built with a conventional design as shown in Figure 7, along with a braking resistor to recoup the heat during the braking of the vehicle.

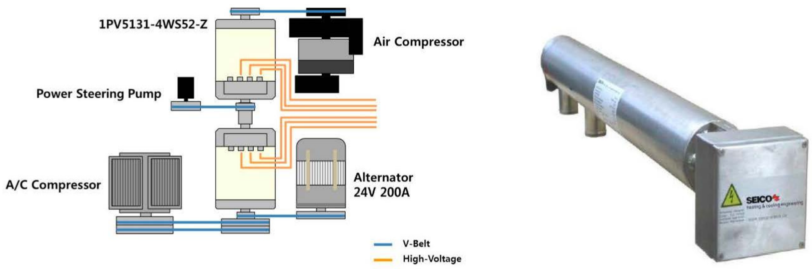


Figure 7. HVAC system and braking resistor.

4.1.2. Test Results

In order to investigate the energy consumption by the HVAC system, the power consumed in each case was measured and the plots from these results are provided in Figure 8. The first case (denoted in green color) was the power consumption without the HVAC operation. The second case was the power consumption with A/C operation at an outside temperature at 30 °C (denoted in red) and the third case was the power consumption with heater operation at an outside temperature at 18 °C (denoted in light blue).

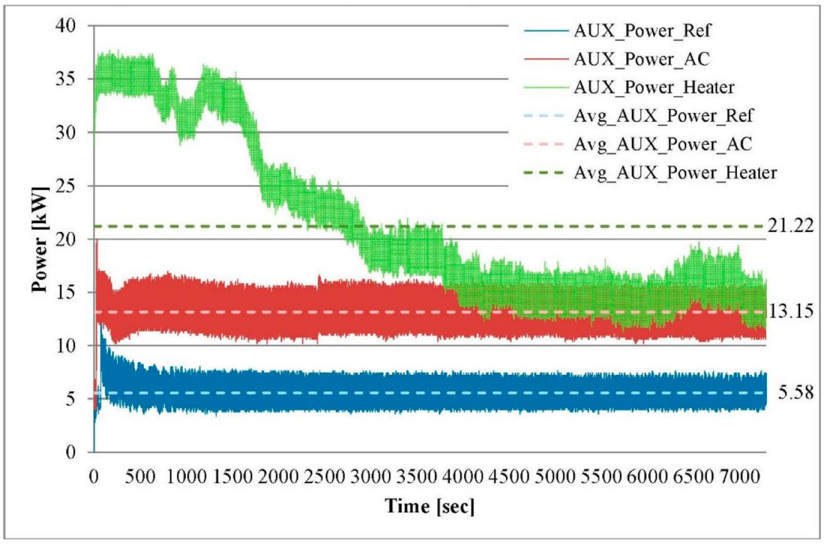


Figure 8. Direct comparison of SOC traces for the Pohang bus route from experiment and simulation.

1. In Figure 8, the green line is for the case without any HVAC operation. At the very early stage of vehicle start-up, about 12 kW of power was consumed to run the compressor for the air tank to support the pneumatic systems in the bus. However, it soon settled down to a range between 4 and 6 kW. Average power consumption for this case was measured to be 5.58 kW.
2. The red line is for the A/C operation case and it showed a power consumption range between 8–18 kW, depending on the situation. Average power consumption was measured to be 13.45 kW.
3. The light blue line is for the case of heater operation and it displayed noticeably high power consumption during the early stages of the operation. This is mainly due to the current heater system which has a braking resistor for the heat recovery from the braking operation. During the early stages of the heater operation, water-glycol in the braking resistor was heated up to 70 °C consuming a high power of 39.5 kw and after that, the heater power consumption settled down to an average of 18 kW. Overall an average power of 21.22 kW was used in the heater operation. This suggests the idea of possibly pre-heating of the braking resistor using the electric power from the grid when the bus is in the garage or at the terminal prior to the normal operation of the bus. This would certainly improve the effective use of the limited battery energy on board.

4.2. Validation of Energy Consumption by Electric Bus

Estimated energy consumption obtained during the initial design process was validated against the actual data obtained from real world driving conditions. A site selected for the pilot program was prepared in a city of Pohang, Korea, as shown in Figure 9. Two battery exchange stations and three electric buses were put in to the pilot program and the bus route within the city was carefully selected to produce a representative driving cycle for a typical inner city public transportation system.

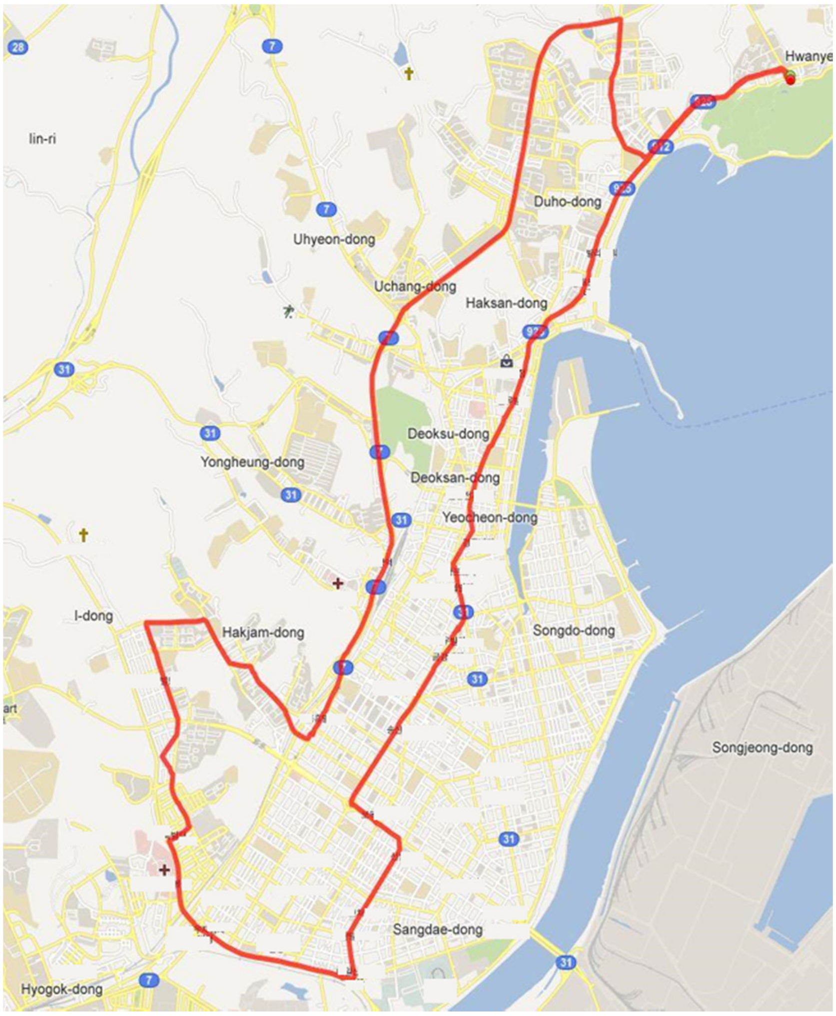


Figure 9. Bus route selected for pilot program.

Over the last few months, the electric buses have generated records of driving performance, driving distance, energy consumption with and without HVAC operation. These collected data were compared with the ones from the energy analysis simulation tool, Autonomie. During the vehicle test, important CAN signals were all logged, in real time, with a CAN analyzer from Vector to understand the driving performance and the energy consumption. More specifically, voltage, current and temperature from the battery pack, location of the vehicle, velocity and a few more operating parameters were collected.

A change of SOC (blue line) from the actual vehicle operation is displayed in Figure 10. A speed profile obtained from the Pohang bus route is overlaid for visually understanding the driving pattern (in red). As shown in Figure 10, SOC started at 84.4% and finished at 44.1% with of total driving distance of 19,538.94 m. The result is summarized in Table 4.

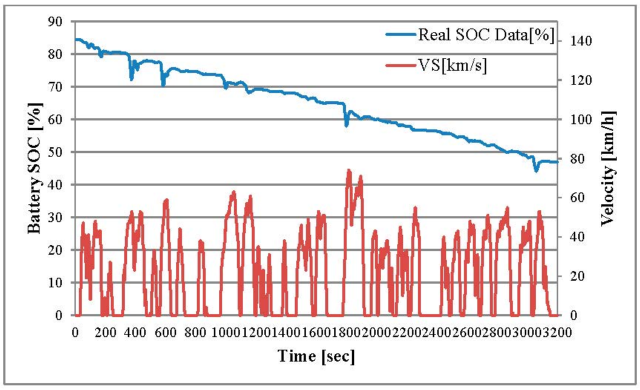


Figure 10. Experimentally measured SOC trace.

Table 4. Summary of experimental results.

Name	Unit	Pohang Bus Route
Process Name	–	Run Pohang Cycle
Cycle Name	–	Pohang Cycle
Cycle Distance	m	19,538.94
Electric Energy Consumption	J/m	4011.89
Initial SOC	%	84.40
Final SOC	%	44.10
Delta SOC	%	−40.30

The same driving cycle was used for the Autonomie model simulation and the results are plotted in Figure 11. Initial SOC was set at 84.4% to make the situation the same as in the case of the vehicle test. With the measured velocity profile, a total of 19,644.17 m was obtained and the SOC was reduced to 46.78%. A summary of the simulation results is displayed in Table 5. Also, a plot of the direct comparison between these two results are provided in Figure 12 and it is clear that the overall behavior from each case were reasonably identical except that five sharp SOC drops were noticed in the case of actual vehicle experimental data (blue line for experimental data and red line for simulated data). As shown in Tables 4 and 5, a SOC of 40.3% was used in the real test and 37.6% was used in the simulation case resulting in a SOC use discrepancy of 2.63%. The average discrepancy of 1.3% was estimated between the SOC traces, with the maximum discrepancy of 10.19% being noticed at 372 s after the start of the driving. Sharp drops noted in the case of actual experiment are thought to be from the noisy voltage and current measurement data resulting in erroneous SOC estimates in the BMS unit.

Table 5. Summary of simulation results.

Name	Unit	Pohang Bus Route Simulation
Simulation folder	–	2013_11_13_23_03_28_783
Process Name	–	Run Pohang Cycle
Cycle Name	–	Pohang Cycle
Cycle Distance	m	19,644.17
Electric Energy Consumption	J/m	3569.53
Initial SOC	%	84.40
Final SOC	%	46.78
Delta SOC	%	−37.67
Percent Regen Braking at Battery	%	58.03
Percent Regen Braking at Wheel	%	84.79

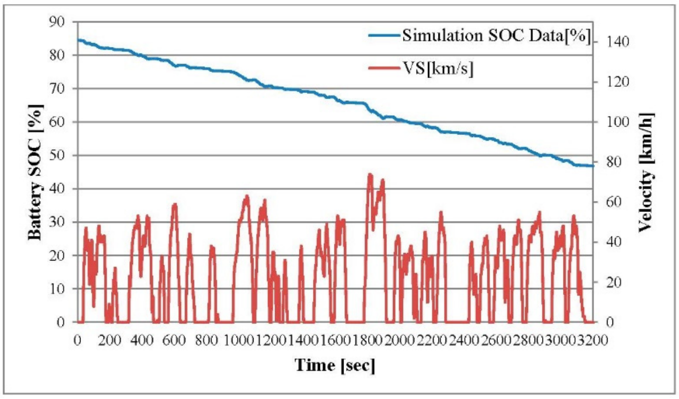


Figure 11. Simulated SOC trace.

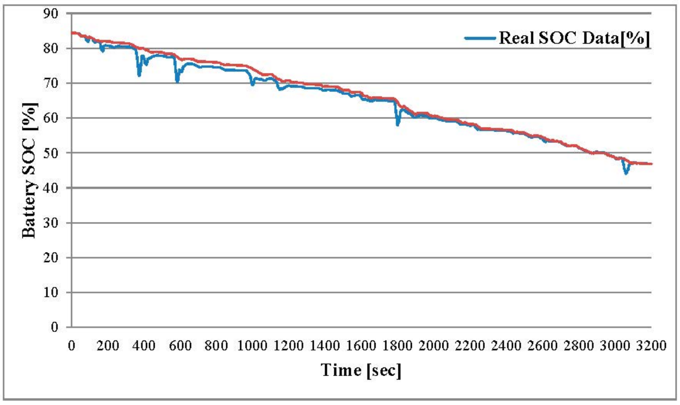


Figure 12. Direct comparison of SOC traces from experiment and simulation.

5. Conclusions

As an effort to address the global warming issue caused by CO_2 emissions and the traffic issue caused by urbanization, an electric bus with a battery exchange system was developed. A major requirement for a public electric transportation system such as quick battery recharging to ensure continuous service was nicely answered with an in-route battery exchange system. The pilot infrastructure and the respective electric bus for the public service was built and experimented on the public road under the real world traffic situations. The electric bus was in service for more than a year and produced valuable data for further refinement of the system. For example, the power consumption by the HVAC system was monitored for many months to provide the design data for future system development. The system clearly provides satisfactory answers to the needs of an electric public transportation system and it is fully expected to become one of the major configurations for a future green public transportation system.

Acknowledgments

This research work was made possible by the fund from Ministry of Land, Infrastructure and Transport of Korea and partially from BK21 Plus program of Korean government and it is gratefully acknowledged by the authors.

Author Contributions

Woongchul Choi designed the overall architecture of the current system as well as the system integration of the electric bus system. Inho Song participated in the interior and exterior design and analysis. Jeongyong Kim carried out the simulation analysis and experimental data acquisition for further validation study.

Conflicts of Interest

The authors declare no conflict of interest.

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