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Development and Performance Evaluation of Advanced Electric Bus Transportation System

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Abstract

Electric buses have superior environmental performance because they emit no CO₂ and other exhaust gases while driving. However, in terms of more popularization of electric buses, it is essential to improve battery performance and realize user-friendliness of charging. To resolve these issues, a concept “short range running and frequent charging” was formulated. Under this approach, the authors have studied methods of greatly reducing the amount of large, heavy, and expensive battery. Research on non-contact inductive power supply (IPS) system has also been conducted as a way of improving charging convenience. A long-term operation test of electric buses was performed in Nagano prefecture as part of a project organized by the Japan Ministry of the Environment from 2011 to 2014. For this project the short-range frequent-charging type electric buses, “Waseda Electric Buses (WEBs)” were developed and tested on public roads to make clear the environmental performance and energy costs. WEB-3, one of the test vehicles, was driven for 41,724 km without any major problems and had advantages to reduce 28 - 42 % of CO₂ emissions and 57 – 64 % of energy costs, compared to conventional diesel buses. And it was estimated on Matlab simulation model that total energy consumption could be reduced by 11 % with vehicle weight reduction, modifications of drivetrain and other components.

Keywords: EV and HV systems, motor drive system, energy management, electric bus, test on public roads

1 Introduction

In order to deal with energy and environmental issues, research and development of electric buses towards improving the environmental performance and the practicability have been conducted by the research group at Waseda University since 2002 [1] [2] [3]. Electric buses have superior environmental performance because they emit no CO₂ and other exhaust gases while driving. However, in terms of more popularization of electric buses, it is essential to

improve battery performance and realize user-friendliness of charging.

To resolve these issues, a concept “short range running and frequent charging” was formulated. Under this approach, the authors have studied methods of greatly reducing the amount of large, heavy, and expensive battery [4] [5]. In addition, research on non-contact inductive power supply (IPS) system has been conducted as a way of improving charging convenience. Thus the authors have researched and have developed practical electric bus “WEB (Waseda Electric Bus)” series [6] [7]. From the point of view of vehicle size and

operation way, small or middle sized buses on regular routes are thought to be suitable and aimed to put into practical use.

From this kind of circumstance, our research group performed a long-term operation test of specially developed electric buses as part of a project organized by the Japan Ministry of the Environment on fixed-route bus in Nagano prefecture for 3 years. The aim of this paper is to assess CO₂ emission and energy cost reduction effect by introducing WEB-3 which is one of the test vehicles and has electric heater, compared to conventional diesel buses. And, to make clear the possibility of further reduction of energy consumption, our research group modified the heating system on WEB-3 and assessed the effect, also explored the possibility of further reduction of running energy on Matlab simulation model.

2 Outline of operation test

2.1 Test vehicle

The test vehicle, WEB-3 was converted from Hino motor company “Poncho” and conversion area was limited as follow in order to save production cost. Diesel engine was replaced with electric motor, clutch / flywheel were removed, and battery was mounted. The exterior of WEB-3 is shown in Figure 1. And major specifications of WEB-3 are shown in Table 1, compared to the base vehicle, “Poncho”. Based on the concept “short range running and frequent charging”, WEB-3 has enough battery to travel short cruising range. Accordingly, vehicle weight and initial cost of WEB-3 is reduced and passenger cabin is still large enough. On the other hand, as a power source, 145 kW permanent magnet synchronous motor is mounted on WEB-3 in order to realize equal traction force to the diesel engine of the base vehicle. 44 kWh battery is manganese Lithium-ion battery which has been successfully used for electric buses and is mounted on rear section of WEB-3. Battery was charged by 30 kW inductive power supply (IPS) systems which were developed for this operation test. And 6 kW electric heating system and cooling system with 3.6 kW motor-driven compressor are mounted on WEB-3.

2.2 Operation routes

The operation test was performed on Gururin-line and Hirabayashi-line. The routes of them are shown in Figure 2 and 3. Gururin-line travels 7.5

km and takes 35 to 40 minutes per service, stopping at Nagano station, Zenkoji (tourism area), Shinshu University, and Nagano Prefectural Government.

Hirabayashi-line travels 10.4 km and takes 40 to 45 minutes one way, stopping at a hospital and residential area. The battery on WEB-3 was charged per service on both lines by IPS (Inductive Power Supply) systems at the parking lot near Nagano station and the base of Nagaden Bus Corporation in Yanagihara.



Figure 1: WEB-3

Table 1: Major specifications of Poncho and WEB-3

Vehicle Name		Poncho	WEB-3
Capacity		31 persons	25 persons
Weight		5,730 kg	6,430 kg
Power Source		Diesel engine	PMSM
Max Power		132 kW	145 kW
Max Torque		490 Nm	400 Nm
Transmission		5-speeds	Only the 3rd gear
Battery	Type	Not	Mn-Li-ion
	Capacity	Applicable	44 kWh

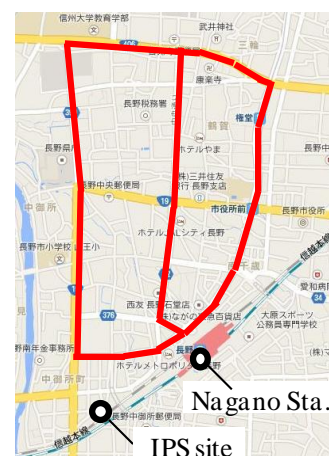


Figure 2: Gururin-line



Figure 3: Hirabayashi-line

3 Results of operation test

3.1 Operation test outline of WEB-3

Operation test outline of WEB-3 is shown in Table 2, monthly and total mileage is in Figure 4. WEB-3 served 1,087 services on Gururin-line from December 2011 to September 2012, and 2,294 services on Hirabayashi-line from December 2012 to January 2014. Total mileage of WEB-3 was 41,724 km. 3 to 4 services were served on Gururin-line and 3 round trips on Hirabayashi-line per day. WEB-3 did not have any major problems on this operation test except the suspension for partial conversion in October and November 2012.

Table 2: Operation outline of WEB-3

Route	Gururin	Hirabayashi
Start	20 Dec. 2011	1 Dec. 2012
End	30 Sep. 2012	31 Jan. 2014
Total mileage km	15,494	26,230
Total passengers	14,205	14,475
Total service	1,087	2,294

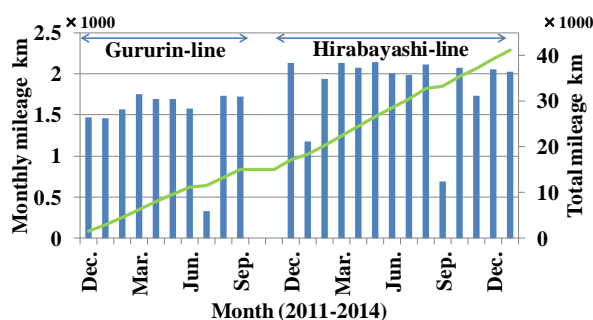


Figure 4: Operation mileage of WEB-3

3.2 Electricity consumption of WEB-3

Total electricity consumption for both HVAC (Heating, Ventilation, and Air Conditioning) and running of WEB-3 is shown monthly in Figure 5.

Average value during operation test was 0.96 kWh / km on Gururin-line and 0.82 kWh / km on Hirabayashi-line.

Electricity consumption for HVAC was 0.21 kWh / km on Gururin-line and 0.16 kWh / km on Hirabayashi-line. The consumption increased in summer and winter because HVAC was used harder. And HVAC consumed more electricity in winter than in summer because of cold climate on this site.

Electricity consumption for running was 0.74 kWh / km on Gururin-line and 0.65 kWh / km on Hirabayashi-line. The reason for this difference is that WEB-3 ran at lower speed and made more stops on Gururin-line than on Hirabayashi-line. In addition, average passenger number per service on Gururin-line was 13 persons and 6 persons on Hirabayashi-line. WEB-3 consumed more electricity for running in winter on both lines. This is because viscosity of gear oil increased driving resistance on cold temperature and studless winter tire increased rolling resistance.

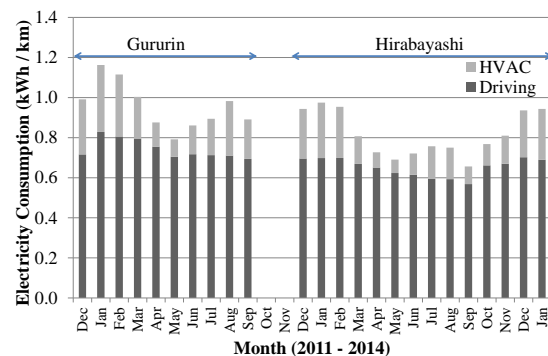


Figure 5: Electricity consumption of WEB-3

3.3 CO₂ emission reduction by introducing WEB-3

Monthly CO₂ emissions of the base diesel bus and WEB-3 are shown in Figure 6. CO₂ emissions in WTW (Well to Wheel) of Diesel bus were 0.83 kg-CO₂ / km on annual average and that of WEB-3 were 0.53 kg- CO₂ / km on average between January and September 2012, then CO₂ emissions were reduced by 36 %. It was shown that CO₂ emissions were able to be reduced by 28~42 % throughout the year by introducing WEB-3.

CO₂ emissions by the diesel bus were calculated by the following numerical formula where CO₂ emission coefficient-WTW of diesel oil was 2.83 kg- CO₂ / ℓ [8] [9].

$$\text{CO}_2 \text{ emission} = \frac{(\text{CO}_2 \text{ emission coefficient-TTW} + \text{CO}_2 \text{ emission coefficient-WTT})}{\text{Fuel consumption}}$$

CO₂ emission coefficient-TTW : 2.64 kg-CO₂ / ℓ

CO₂ emission coefficient-WTT : 0.19 kg-CO₂ / ℓ

CO₂ emissions by WEB-3 were calculated with CO₂ emission coefficient of electricity: 0.473 kg-CO₂ / kWh announced by Chubu Electric Power Co., Ltd in 2010 and without adjustment by the Kyoto Mechanism [10]. Electricity consumption was measured at AC 200V co-operative power, considering charging efficiency. Measured value of that efficiency was 85 %.

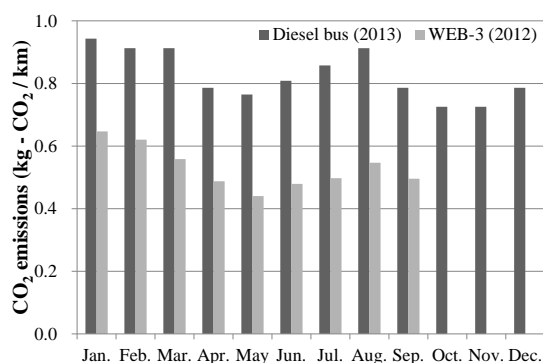


Figure 6: CO₂ emissions of Diesel bus and WEB-3

3.4 Energy cost reduction by introducing WEB-3

Monthly energy costs of the base diesel bus and WEB-3 are shown in Figure 7. Fuel costs for the diesel bus were 31.6 yen / km on annual average and electricity costs for WEB-3 were 12.8 yen / km on average between January and September 2012, then energy costs for operation were reduced by 59 %. It was shown that energy costs were able to be reduced by 57 – 64 % throughout the year by introducing WEB-3.

These results were calculated with the price of diesel oil : 108.3 yen / ℓ and that of electricity : 11.4 yen / kWh.

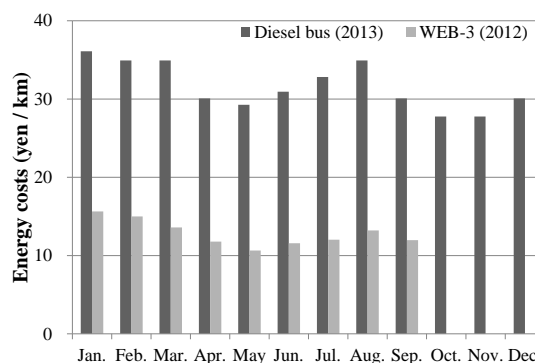


Figure 7: Energy costs of Diesel bus and WEB-3

4 Possibility of further reduction of CO₂ emission and energy cost

It is possible to reduce total energy consumption by the vehicle modification. Some measures including HVAC and vehicle system technologies for WEB-3 are discussed.

4.1 HVAC energy reduction

The powertrain of electric bus has high efficiency and then HVAC energy accounts for a large percentage of total energy consumption. On WEB-3, HVAC energy accounted for about 20 % of total energy consumption. And CO₂ emission and energy cost reduction by introducing WEB-3 decreased in winter because electric buses cannot use engine exhaust heat for heating in the passenger compartment.

To resolve this issue, questionnaires about interior environment were performed in order to make clear the problems of WEB-3's heating system. As a result, the following problems were reported.

Firstly, there was a gap between the comfortable temperature for drivers and that for passengers. Drivers tended to feel cold because they were not allowed to wear thick overcoats and heat insulation around the driver's seat was inadequate. On the other hand, passengers wore thick overcoats and gloves. So they did not feel cold as much as drivers.

Secondly, drivers tended to let heater work too much from the above circumstance. And many passengers rode on WEB-3 for a few minutes and kept wearing their overcoats. So many passengers said that interior temperature of WEB-3 was too hot for them.

According to the above results, it was important to secure warm environment for the driver's area and then save heating power in optimizing heating system of WEB-3. That would realize HVAC energy reduction and more comfortable environment for the passenger compartment.

Therefore, a seat heater was introduced on the driver's seat to secure warm environment for drivers. Appearance of a seat heater is shown in Figure 8. Seat heaters are able to warm drivers quickly and by less energy (Power of the seat heater on WEB-3 was 60W) because they are closely fitted to drivers' bodies.



Figure 8: Seat heater on driver's seat

In order to verify the effect of introducing seat heater, various data before and after the introduction are shown in Table 3. There is little difference on outside temperature but inside temperature decreases by 3 °C. This is because seat heater secured warm environment for drivers and then they saved heating power.

After introducing a seat heater, questionnaires about interior environment were performed again and many passengers said that interior temperature of WEB-3 was comfortable. This result shows that the seat heater realized HVAC energy reduction and more comfortable environment for passengers. Heating energy was decreased from 0.38 kWh / km to 0.35 kWh / km, 9.4 % reduction, by introducing the seat heater. Total CO₂ emissions and energy costs including running were reduced by 3.8 %.

Table 3: Effect by introducing seat heater

Comparison items	Before introduction	After introduction	Reduction rate
Electricity consumption for HVAC	0.38 kWh / km	0.35 kWh / km	-9.4%
Outside temperature	0.4 °C	0.6 °C	-
Inside temperature	25.4 °C	22.4 °C	
CO ₂ emissions	0.54 kg-CO ₂ / km	0.52 kg-CO ₂ / km	-3.8%
Energy costs	13.0 yen / km	12.5 yen / km	

4.2 Possibility of running energy reduction

Possibility of running energy reduction was estimated by Matlab simulation model.

On this model, traction force, motor power, battery power, and electricity consumption is calculated by inputting vehicle speed, taking vehicle weight, rolling resistance, and air resistance into consideration. On simulation, HVAC was not used and electricity consumption for auxiliary equipment was set at 0.866 kW that was measured value on the operation test. The number of passengers was set at 14 persons that were calculated by adding 1 driver to average passenger number 13 persons. Major parameters on simulation are shown in Table 4.

Table 4: Major parameters on simulation

Vehicle Weight	6430 kg
Boarding number of persons	14 persons
Vehicle gross weight	7200 kg
Overall gear ratio	11.6
Frontal projected area	5.91 m ²
Tyre radius	0.356 m
AUX power	0.866 kW
Driving route	Gururin-line

4.2.1 Accuracy of simulation model

Running energy consumption of WEB-3 on Gururin-line was 0.741 kWh / km on average between December 2011 and September 2012. On the other hand, the value calculated by the simulation model was 0.746 kWh / km. Both values did not include electricity consumption for HVAC. From this result, this simulation model was thought to be accurate enough to verify the possibility of running energy reduction.

4.2.2 Vehicle weight reduction

Possibility of running energy reduction by vehicle weight reduction was calculated.

Figure 9 shows the running energy reduction by vehicle weight reduction on WEB-3. When the vehicle gross weight is reduced by 10 %, the running energy is reduced by 8.3 %. On WEB-3, air resistance accounts for a small percentage because fixed route buses run at low speed. Therefore vehicle weight reduction successfully effects the running energy reduction on fixed route buses.

It is estimated that the weight of WEB-3 could be reduced by 650 kg by improving the specific energy of the battery and simplifying the drivetrain

system. And then the running energy of WEB-3 on Gururin-line could be reduced by 7.5 %.

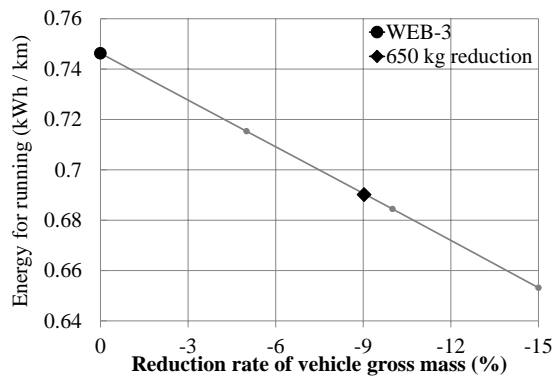


Figure 9: Relationship between vehicle gross mass and energy consumption for running

4.2.3 Optimization of overall gear ratio

Possibility of running energy reduction by optimizing overall gear ratio was discussed.

Figure 10 shows how the running energy changes by increasing and decreasing overall gear ratio from 11.6 of WEB-3. When the overall gear ratio is set at 17.6, the running energy becomes minimum value. And then the running energy of WEB-3 on Gururin-line could be reduced by 2.1 %.

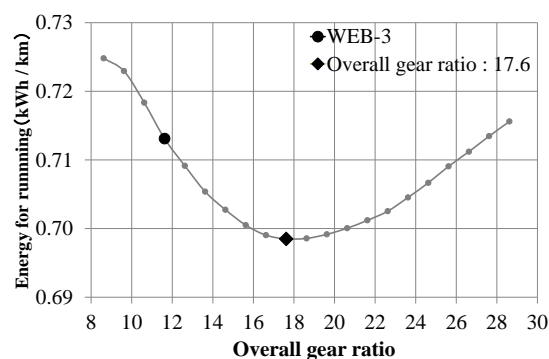


Figure 10: Relationship between overall gear ratio and energy consumption for running

Figure 11 shows how the working points of the motor change by increasing overall gear ratio from 11.6 to 17.6. Motor gets to work on lower load and higher speed area by changing overall gear ratio. That would enable WEB-3 to regenerate energy in more situations and on higher rotation speed. It is estimated, on simulation model, that regeneration energy of WEB-3 on Gururin-line could be increased from 0.029 kWh / km to 0.10 kWh / km. On the other

hand, changing overall gear ratio would also effect torque fluctuation. Therefore, if torque control to keep riding comfort is realized, there will be a possibility of increasing regeneration energy by optimizing overall gear ratio.

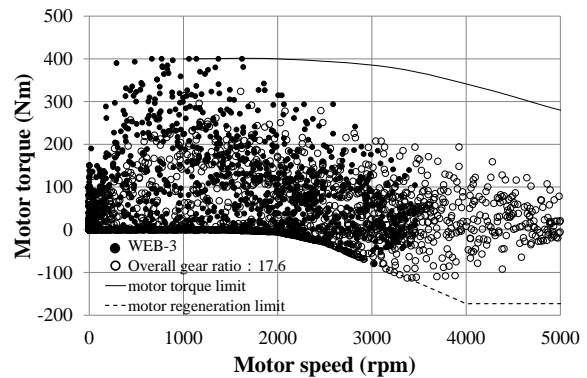


Figure 11: Relationship between overall gear ratio and motor working points

4.2.4 Change of regeneration torque limit

Possibility of running energy reduction by changing regeneration torque limit was calculated.

Figure 12 shows the motor working points at deceleration on Gururin-line, WEB-3's regeneration torque limit, and modified one. Most of the motor working points are under the regeneration torque limit on WEB-3 and the deceleration energy is not regenerated well. Then, the regeneration torque limit is modified as follow. Regeneration starts from lower speed and regeneration torque increases, in accordance with motor rotation speed, up to maximum torque that is 70 % of WEB-3.

It was calculated that the regeneration energy could increase from 0.029 kWh / km to 0.043 kWh / km, 46 % increase by changing the regeneration torque limit. And then the running energy of WEB-3 on Gururin-line could be reduced by 1.9 %.

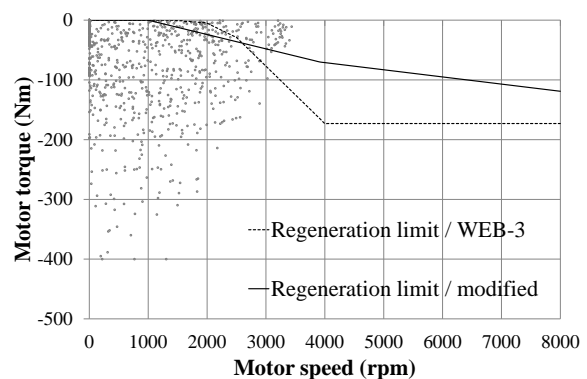


Figure 12: Change of regeneration torque limit

4.3 Effect of HVAC and running energy reduction

CO₂ emission and energy cost reduction effect by HVAC and running energy reduction was calculated.

On HVAC energy of WEB-3, the heating energy was reduced by 9.4 % by introducing a seat heater on driver's seat. And it was estimated that the running energy could be reduced by 7.5 % by vehicle weight reduction, 2.1 % by optimizing overall gear ratio, and 1.9 % by changing regeneration torque limit, 11.5 % totally.

Figure 13 and 14 show CO₂ emission and energy cost reduction effect by the above improvement plans in January when CO₂ emission and energy cost reduction by introducing WEB-3 was minimum amount. Total electricity consumption for both HVAC and running is 1.04 kWh / km that is reduced by 11 % compared with WEB-3, 1.16 kWh / km. This could enable CO₂ emission reduction on Gururin-line to improve from 31 % to 39 % and energy cost reduction from 57 % to 61 %.

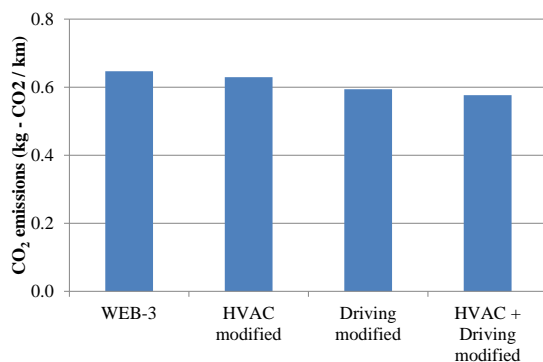


Figure 13: Estimation of CO₂ emission reduction

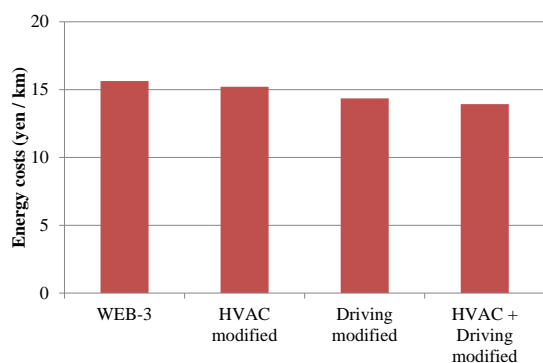


Figure 14: Estimation of energy cost reduction

5 Conclusion

The short-range frequent-charging type electric buses, “Waseda Electric Buses (WEBs)” were developed and a long-term operation test was performed to assess their practicability and environmental performance in Nagano prefecture for 3 years. The obtained results are as follows:

(a) Electric buses have shown enough performance including driveability and cruising range for city bus on a regular route. WEB-3 travelled 41,724 km and served 3,381 services for 3 year-commercial operation. Also, there was no major problem during operation and the reliability of WEB-3 was confirmed.

(b) Total electricity consumption for both HVAC and running was 0.96 kWh / km on Gururin-line and 0.82 kWh / km on Hirabayashi-line. Electricity for HVAC accounted for about 20 % and that for running did for about 80 %.

WEB-3 enabled CO₂ emissions to be reduced by 28 – 42 % and energy costs by 57 – 64 % compared to conventional diesel buses.

(c) Possibility of reducing energy consumption was discussed. It was suggested that total energy consumption for both HVAC and running could be reduced by 11 % by modifying heating system, reducing vehicle weight, and simplifying drivetrain.

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