EVS26
Los Angeles, California, May 6-9, 2012

On-road Performance Evaluation of the "WEB 1 Advanced" Short Range, Frequent Charging Electric Micro Bus

Thomas Pontefract[1], Kimiyoshi Kobayashi[1], Kazuaki Seki[1], Yushi Kamiya[1], Yasuhiro Daisho[1], Yu Saito[2], Shunsuke Takahashi[3]

[1]*Graduate School of Environment and Energy Engineering, Waseda University, 55S-704, 3-4-1 Ohkubo, Shinjuku, Tokyo, JAPAN, E-mail: tspontefract@asagi.waseda.jp*
[2]*Waseda Research Institute Corporation*
[3]*Showa Aircraft Industry Co., Ltd*

Abstract

This paper reports on the development of the Waseda Electric micro Bus (WEB). The bus features a non-contact inductive power supply (IPS) system to enable rapid, safe and convenient charging. On-road tests were carried out to verify the practicality of the short range, rapid charging concept, and to determine improvements in environmental performance over a conventional bus. Across three different road tests, significant improvements of between 38% and 68% in CO_2 emissions were found.

Keywords: bus, EV (electric vehicle), lithium battery, wireless charging, public transport

1. Introduction

In recent years, there are have been increasing demands on automobile manufacturers to develop vehicles incorporating a clean power source to replace the conventional internal combustion engine. Among others, research and development of battery-electric vehicles has garnered much attention in recent years.

However, the adoption of electric automobiles remains slow. This is due to issues concerning the performance of vehicle batteries, such as the fact that the driving range of an electric automobile on a single battery charge does not equal that of an automobile with an internal combustion engine, the high costs associated with electric automobile batteries, and the long recharge times of these batteries [1].

Therefore, this laboratory has created an electric-powered micro bus called the Waseda Electric Bus (WEB), shown in Fig. 1, by modifying a Poncho diesel micro bus manufactured by Hino Motors, Ltd. with the goal of developing a vehicle with superior environmental performance [2]. In creating the WEB, no modifications were made to the body of the base vehicle. The plan was to convert the bus into an electric-powered vehicle by replacing the diesel engine with an electric motor and installing a ZEBRA (Na-NiCl_2) battery system [3].

Figure 1: Waseda Electric micro Bus (WEB)

The concept for the WEB is short range and frequent charging. The aim is to minimize battery weight and cost by installing the smallest battery possible. The driving range of the vehicle is limited by the smaller battery, but this shortfall is compensated for by charging the battery very frequently and, by adopting an inductive power supply (IPS) system, charging can be carried out safely and quickly [4]. Test runs have been already made with the WEB in several regions in Japan, including Honjo, Mitaka, Akishima, Shinjuku, Sakai, Nara, Moriyama, Sakura, and Nakanoshima, and the environmental performance of the WEB and its battery charging performance have been verified. The improvement in environmental performance over a diesel bus was clear, but issues remained with respect to charging performance.

To address this, the sodium battery was exchanged for a Li-ion battery. In order to evaluate the effectiveness of this change, battery charge acceptance tests were performed using the IPS system. Then, testing was performed on public roads in Nara, Yukarigaoka (Chiba Prefecture) and Oze (Gunma Prefecture) to evaluate the vehicle's overall performance after the change of battery.

This paper describes the improvement in performance due to the change of battery and assesses of the feasibility and environmental performance of the short range, frequent charging concept based on the aforementioned road tests.

2. Creation of New Vehicle and Battery Charging Device

The sodium ZEBRA battery that was previously installed in the WEB was replaced with a Li-ion battery in order to solve the charging performance problem described in the previous section. This new vehicle was dubbed the WEB-1 Advanced (WEB1-adv.) to differentiate it from the previous WEB vehicle and its specifications are shown in Table 1.

In addition, an IPS system was installed on the new vehicle with the aim of charging the battery safely and quickly. The system is composed of two coils. One coil is installed on the road surface and the other coil is installed on the vehicle. The device charges the vehicle battery via electromagnetic induction.

A new IPS base unit, shown in Fig. 2, was also fabricated, made principally from concrete to withstand the weight of the vehicle and so minimize the risk of damage in real world use.

3. 30 kW Charge Acceptance Test Using IPS System

In order to evaluate the effectiveness of the battery change, the battery was charged at 30 kW, which is the maximum output of the IPS system, and the charge acceptance performance was confirmed. In this test, the battery was charged from the practical lower limit of 20% up to 100%.

The battery charging system using the IPS system on the WEB1-adv charges the battery with constant power (CP charge) until the battery voltage reaches the upper limit voltage (Nickel Sodium Chloride Battery: 306 V, Li-ion: 323 V). After this it continues to charge the battery with constant voltage (CV charge) until the battery reaches a state of charge (SOC) of 100%. During CV charge the current decreases as SOC rises, causing the

Table 1: Vehicle specification

		Base Vehicle	*WEB*	*WEB 1-adv.*
Size(L×W×H)		5770×1995×2830 mm		
Prime mover	*On-board Unit*	Diesel - 2.8L	IPM Motor	
	Max. Power	93 kW	50 kW	
	Max. Torque	294 m	240 Nm	
Battery	*Type*	-	Na-$NiCl_2$ Battery	Li-ion Battery
	Energy Density	-	105 Wh/kg	60 Wh/kg
	Power Density	-	180 W/kg	285 W/kg
	Max. Power	-	32 kW	56 kW
	Capacity	-	18.9 kWh	12.0 kWh
	Mass	-	180 kg	198 kg
IPS	*Max. Power*	-	30 kW	
	Air Gap	-	100 mm	
	Material	-	CFRP	Concrete

Figure 2: Inductive Power Supply (IPS) base unit

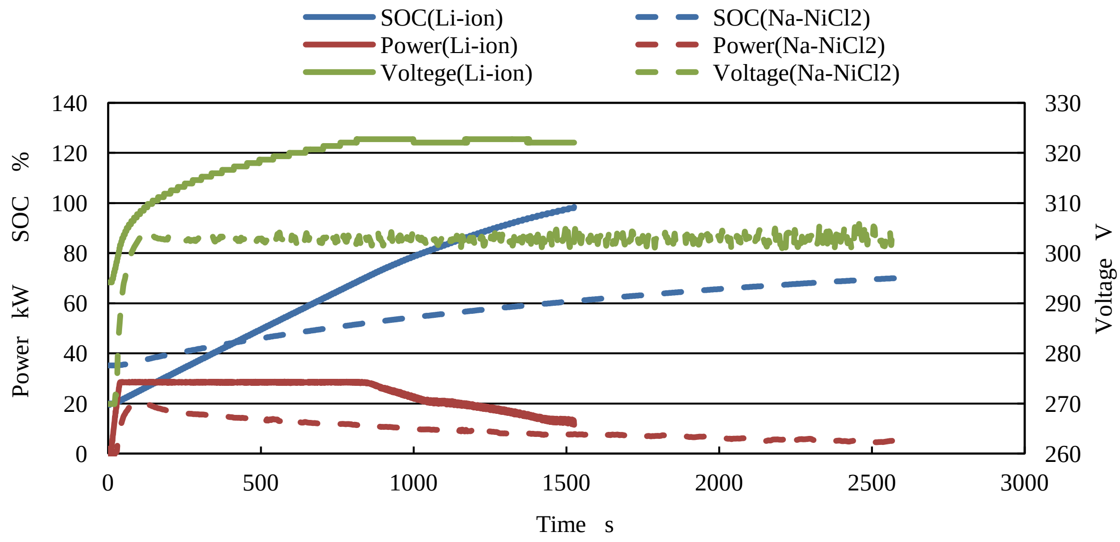


Figure 3: Battery test results

charging power to also decrease. Therefore, a battery that can sustain CP charging for longer is desirable.

The results for both the old and new batteries are shown in Fig. 3. The sodium battery reached its voltage limit very quickly, and switched to CV charging at around 60 seconds. As a result, there was almost no CP charging, and the maximum charging power was limited to about 20 kW, not fully utilizing the performance of the IPS system. In comparison, the Li-ion battery did not reach the upper limit voltage until SOC had reached 70% and was able to conduct CP charging at 30 kW. From this it can be concluded that the Li-ion battery was able to fully utilize the performance of the IPS system.

Thus, switching from the sodium battery to the Li-ion battery enabled a clear improvement in charging performance.

4. On-road performance tests

To evaluate the real life performance of the WEB1-adv, tests were carried out on actual bus routes in Nara, Yukarigaoka (Chiba prefecture) and Oze (Gunma prefecture). Power consumption and battery temperatures were monitored in order to test the feasibility of the charging model in these situations.

4.1 Nara

The WEB1-adv was tested first in Nara. The bus was used on a tourist loop bus route in Nara Park, 5.5km in length. IPS base units were placed at two locations, one at the beginning/end point of the route and one partway along. The halfway charge was carried out in the time passengers were embarking and disembarking. This provided an opportunity to test the feasibility of using IPS charging for stop-by-stop range extension.

4.1.1 Test route and conditions

The test route, shown in Fig. 4, includes the famous Todaiji temple and Kasuga Shrine. The start/end point and first IPS unit were placed at the Nara Prefectural Government Office, and the halfway charge was carried out at the Kasuga Shrine bus stop. As this area is a park popular with tourists, a bus with a minimal environmental footprint is desirable.

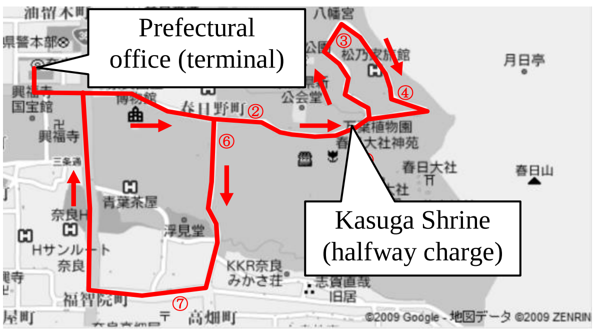


Figure 4: Nara test route

The parameters for the test were the charging time at the Kasuga Shrine stop (no charge, 1 or 2 minutes' charge), and the status of the bus' air conditioning system (off, or at maximum power). On arrival at the Prefectural office, the battery was charged to SOC 70%. The test conditions are shown in Table 2.

Table 2: Test conditions for Nara test

Test No.	A/C	Charge	
		Kasuga Shrine	Prefectural Office
1	OFF	-	SOC ≦ 70%
2	MAX	-	
3	OFF	1min.	
4	MAX	1min.	
5	OFF	2min.	
6	MAX	2min.	

4.1.2 Results of Nara Test

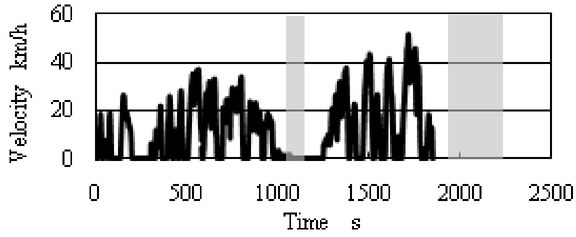
The WEB1-adv ran 6 laps of the route. Fig. 5 shows the results of test number 3, in which the bus was charged for 1 min at Kasuga Shrine and the air conditioning was switched off. The grey blocks indicate charging periods. As shown in Fig. 5a, the 5.5km route took approximately 30 minutes to complete.

Fig. 5b shows the SOC profile of the route from departure, to the completion of charging at the end point. Around the 1100 second mark the halfway charge is carried out, and an increase in SOC is seen. The charging power at this point is visible in Fig. 5c. From around 1900 seconds onwards, charging at the end point of the route is visible. Around 6 minutes was required to restore SOC to 70%. This means that 6+1 minutes of charging per lap are all that are required for continuous operation on the 5.5.km route. The bus can spend much more time on the road than at the charging station, so the feasibility of the short range frequent charging model is confirmed in this case.

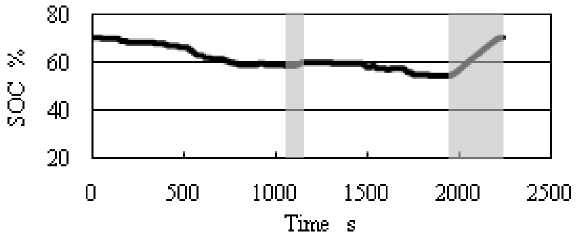
However, the system in its current state cannot provide 30kW of power to the battery instantaneously; as we saw in Fig. 3, it takes a short time to build up. As such, the longer charge at the end of the run is able to provide much more power per second on average than the halfway charge, suggesting that charges on the order of a few minutes are more effective and very short charges are perhaps of limited usefulness.

Battery temperatures before and after each run and each base charge are shown in Table 3, and the temperature rise of each battery module during test 3 is shown in Fig. 6. The WEB1-adv battery is composed of 11 modules. From Table 3, we can see a temperature rise of 1-2°C per lap when the vehicle is running, and 1-4°C during IPS charging. Battery temperatures steadily rose to 42°C by the end of the final charge, but the Li-ion battery installed in the WEB1-adv only detects temperatures above 65°C as abnormal, so the battery temperature remained well within acceptable limits.

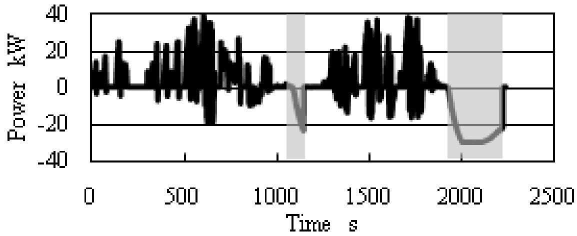
The temperature rise is most likely due to the lack of active cooling; no fan is installed in the battery compartment, and this allows a buildup of heat. In extended periods of use, it may be possible to utilize active cooling measures to mitigate this and allow the run/charge cycle to be repeated indefinitely.



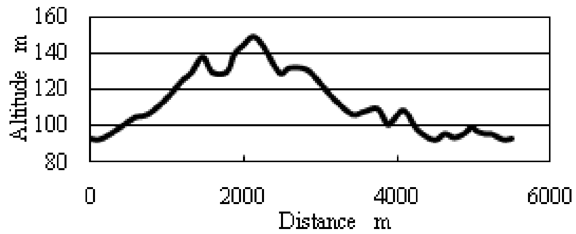
a) Velocity



b) SOC



c) Power



d) Elevation

Figure 5: Nara test results (test no. 3)

Table 3: Battery Temperature Rise

Test No.	Run				IPS			
	Temperature °C			Time s	Temperature °C			Time s
	Start	End	⊿T		Start	End	⊿T	
1	19	20	1	2646	20	22	2	413.0
2	24	26	2	2309	26	28	2	494.6
3	29	30	1	1856	30	32	2	312.5
4	32	33	1	2227	33	37	4	752.3
5	37	38	1	2134	38	39	1	227.9
6	39	40	1	2176	40	42	2	388.1

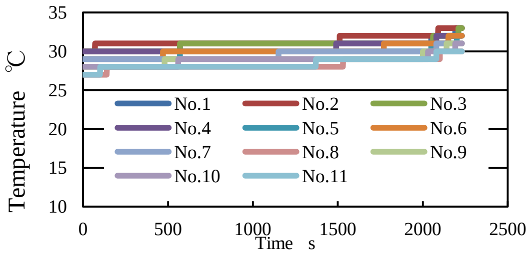


Figure 6: Temperature rise for each battery module

The rate of effective CO_2 emission for each of the six runs is shown in Fig. 7, based on a figure of 0.299kg-CO_2/kWh [5]. This is the value given by the Kansai Electric Power Company (KEPCO), who supply power to this part of Japan. The lowest rate achieved was 0.120kg-CO_2/km. By comparison, the diesel bus upon which the WEB1-adv is based achieves 0.370 kg-CO_2/km on the M15 test mode. The M15 test mode's average speed is 15km/h, and does not include any slopes, while the average speed of the Nara test was closer to 10km/h and the test route had a height variation of around 60m (see Fig. 5 d)). Thus, even under the considerably stricter test conditions of the Nara test, the WEB1-adv achieved a 67.6% reduction in emissions over the diesel bus.

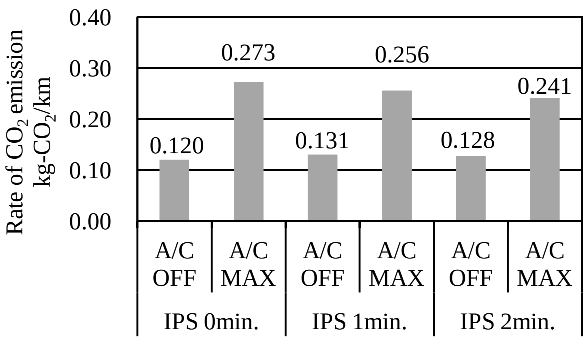


Figure 7: Rate of CO_2 emission

4.2 Yukarigaoka

4.2.1 Test route and test conditions

On this occasion, the test route was a circuit of the Yukarigaoka residential area in Chiba prefecture, shown in Fig. 8. The city is actively pursuing environmental initiatives. Currently, the main public transport link in the area is the Yamaman Yukarigaoka monorail line. This test supposes the electric micro bus to be an auxiliary transport service supporting the main public transport network.

The base bus stop was located at the Chugakkou station, and the bus was, again, charged to 70% SOC at the end of each lap. The elevation profile, shown in Fig. 9, shows a height variation of about 12m, making this route much flatter than the Nara test route.

The air-conditioner load was used as a variable, and was set either off or to maximum load. The test conditions are shown in Table 4.

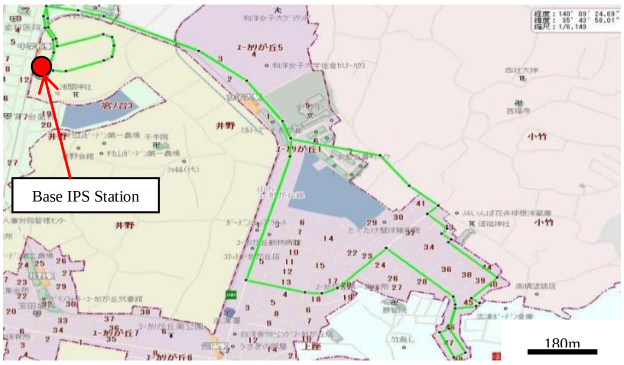


Figure 8: Yukarigaoka test route

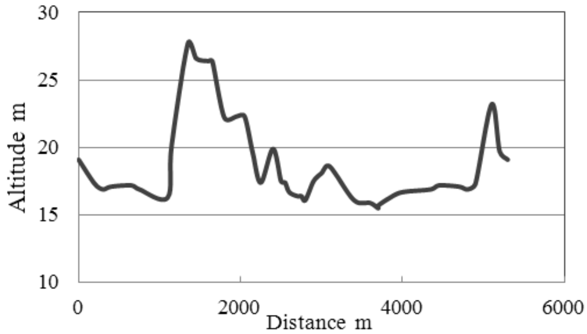


Figure 9 : Height profile of route

Table 4: Test conditions

Test No.	*A/C*	*Charge*
1	OFF	SOC≦70%
2	OFF	
3	OFF	
4	OFF	
5	ON	
6	ON	
7	ON	
8	ON	

4.2.2 Results of Yukarigaoka test

In this test the WEB1-adv was driven on the test route a total of eight times. The results obtained from tests 4 and 8 are shown in figures 10 and 11 respectively. The vehicle was driven for one lap along the 5,24 km route at the speeds shown in Fig. 11 a) and Fig. 12 a), and around 25 minutes was required to complete the route.

Battery power results are shown in Fig. 11 b) and Fig. 12 b). Negative values are due to the regenerative braking function of the vehicle. We can see that the battery was charged at up to 30kW, the maximum power transmission capability of the IPS. The reduction in SOC over the route is approximately 25% with A/C on, as shown in Fig. 12 c).

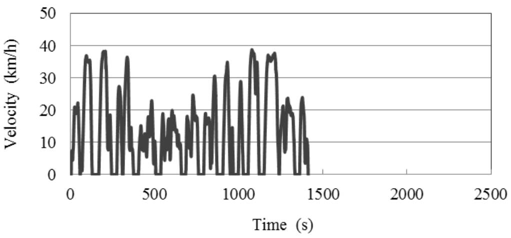
This result means that power consumption during operation is increased 1.6 times by using A/C.

Charging time is approximately 7 minutes with A/C off (Test No. 4), and approximately 9 minutes with A/C on (Test No. 8). The average time of IPS charging was 9 minutes in this test. This confirms that the short-distance, frequent-charging model is feasible in this setting, but it also shows that A/C has a significant effect on mileage and CO_2 emissions.

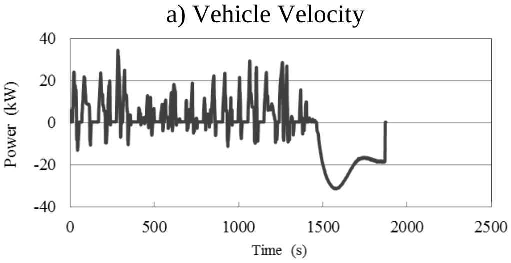
Changes in battery temperature due to vehicle operation, and due to battery charging via IPS are shown in Table 5 and Table 6 respectively. Detailed charts of the rise in battery temperature in each of the 11 battery modules during the test are shown in Fig. 12, and Fig. 13, with each module represented by a different color.

It can be confirmed from Table 4 that the battery temperature varies by no more than 1 ºC with each lap that the vehicle runs. It can also be confirmed that the battery temperature rises by 1 to 5 ºC when the battery is charged with the IPS system. Ultimately, the battery temperature rose to 37 ºC after 4½ hours of continuous running and charging cycles but again, this is well within safe limits.

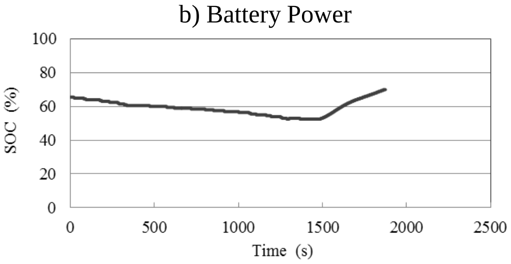
Fig. 14 shows the rate of CO_2 emissions calculated from the test results. The specific CO_2 emissions value used here is 0.324 kg-CO2/kWh, as given by the Tokyo Electric Power Company, who supply Chiba prefecture [6]. As in the Nara test, the average speed was slower than the M15 mode, and there were some changes in elevation, making the test conditions stricter than the M15 mode. The lowest rate of CO_2 emissions recorded in this test was 0.118 kg-CO_2/km with A/C off, and 0.229 kg-CO_2/km with A/C on, compared with 0.370 kg-CO_2/km (7.40 km/l diesel) for the diesel bus on the M15 mode. This is a reduction of 68.1% with A/C off, and 38.1% with A/C on. It can thus be concluded that running the WEB rather than a comparable diesel bus on public roads can reduce greenhouse emissions.



a) Vehicle Velocity

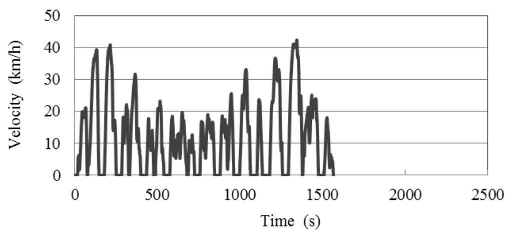


b) Battery Power

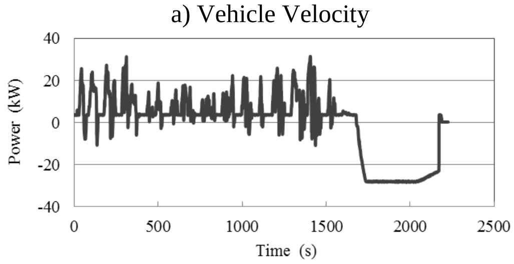


c) SOC

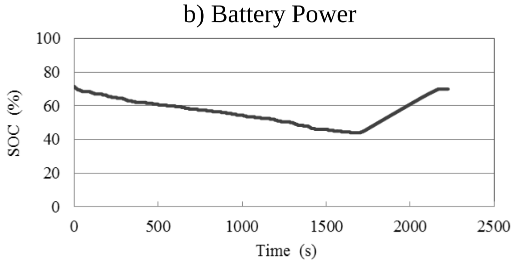
Figure 10: Yukarigaoka test results (test no. 4, A/C off)



a) Vehicle Velocity



b) Battery Power



c) SOC

Figure 11: Yukarigaoka test results (test no. 8, A/C on)

Table 5: Battery temperature rise (running)

Test No.	A/C	Running			
		Temperature degree C			Time s
		Start	End	ΔT	
1	OFF	14	15	1	1336
2	OFF	16	17	1	1509
3	OFF	19	19	0	1467
4	OFF	20	20	0	1413
5	ON	22	23	1	1484
6	ON	28	29	1	1719
7	ON	31	31	0	1725
8	ON	35	34	-1	1566

Table 6: Battery temperature rise (IPS charging)

Test No.	A/C	IPS			
		Temperature degree C			Time s
		Start	End	ΔT	
1	OFF	15	16	1	170
2	OFF	17	18	1	503
3	OFF	19	20	1	189
4	OFF	20	22	2	460
5	ON	23	28	5	1020
6	ON	29	31	2	495
7	ON	31	34	3	979
8	ON	34	37	3	660

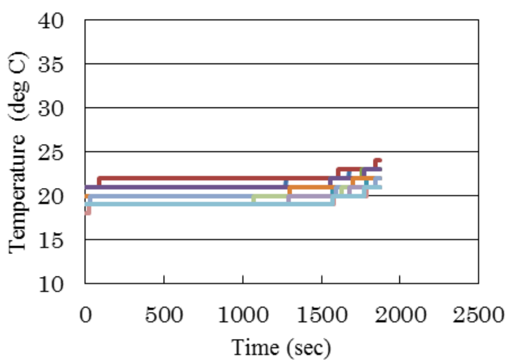


Figure 12: Battery module temperatures (test 4)

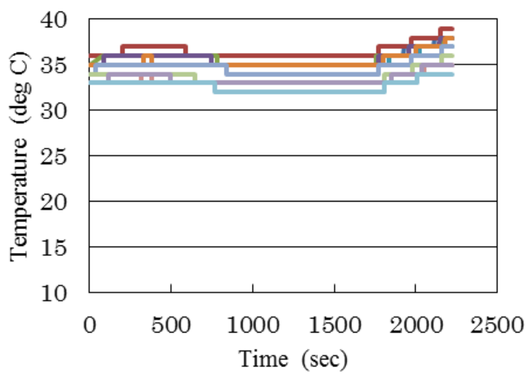


Figure 13: Battery module temperatures (test 8)

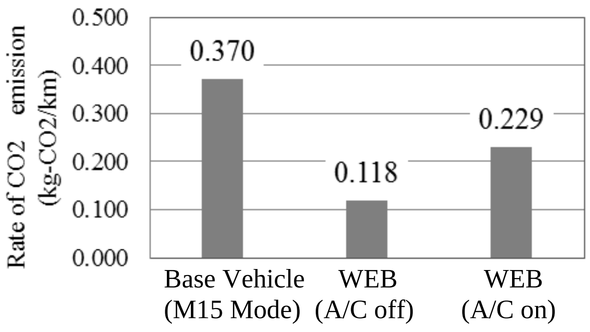


Figure 14: CO_2 emission rates

4.3 Oze

4.3.1 Test route and conditions

A test of power consumption and battery temperature was carried out on a 3.2km stretch of gravel road in the Oze National Park, rising from an altitude of 1180m to 1420m. This linear route, shown in Fig. 15, links the national park visitors' center at Oshimizu with a trailhead and rest area at Ichinose. The height profile of this route is shown in Fig. 16. IPS charging was carried out at the Oshimizu terminus at the end of each run. The route is well-used by hikers and this foot traffic, combined with the electric bus' almost total lack of audible noise, meant that speed had to be limited to about 15km/h for safety reasons.

Figure 15: Oze test route

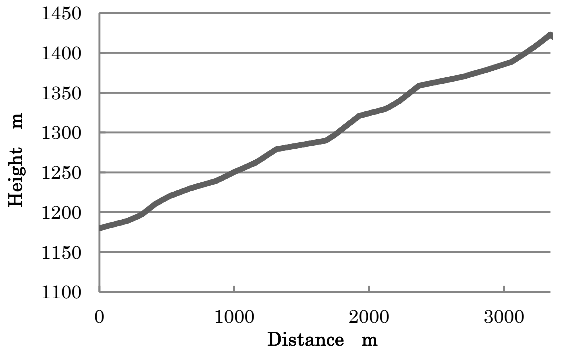


Figure 16: Height profile of Oze test route (outward)

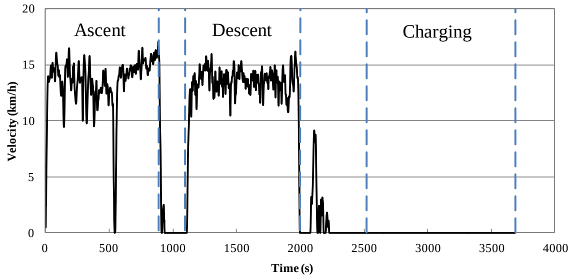
The bus was driven on a round-trip of the route, recharging to 100% SOC via IPS at the terminus. Air conditioning remained switched off throughout the test.

4.3.2 Results of Oze test

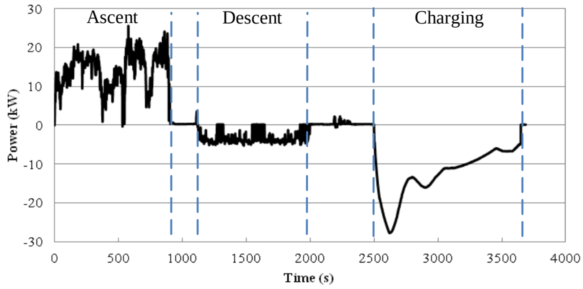
Two runs were completed, and the results of the second are shown in Fig. 17. Fig. 17 a) shows the speed profile of the run. The short series of spikes around 2100 seconds shows the maneuvering of the bus into position over the IPS base unit. Fig. 17 b) shows battery power over the length of the run. The power consumption during ascent and regenerative braking during the descent are clearly visible. The change in SOC is shown in Fig. 17 c), and the partial recovery of SOC can be seen during the descent period.

Power consumption on the climbing section of the journey was 0.786km/kWh, but for the outward and return sections combined, the contribution of regenerative braking brought this up to 1.93km/kWh. This equates to an effective CO_2 emissions rate of 0.189kg-CO_2/km, which is higher than in the previous tests. This can be attributed to the energy expended climbing the steep course, limitations of the regenerative braking system which prevented much of this energy being recovered on the downward leg, and higher rolling resistance due to the rough gravel road surface.

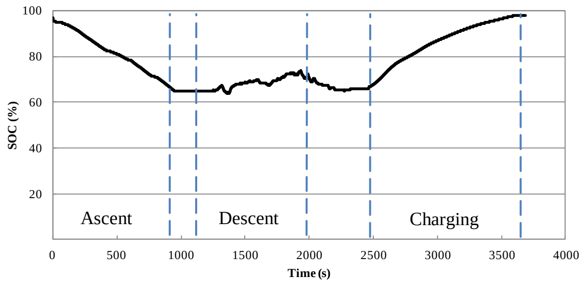
Changes in battery temperature are shown for each run in tables 7 and 8 , and the temperatures of each module are shown in Fig. 18. As in the previous tests, temperature rises of as much as 4ºC were observed during both running and IPS charging, but temperatures did not approach 65ºC. At least for a single return run, the rise in battery temperature does not call for anything more than natural, passive cooling for the batteries, but the temperature rise could prove problematic during extended periods of continuous use.



a) Vehicle Velocity



b) Battery Power



c) SOC

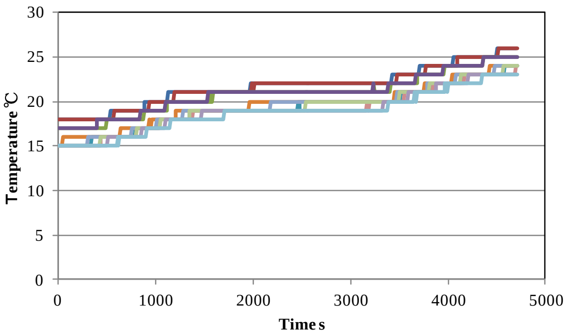
Figure 17: Oze test results (2nd run)

Table 7: Battery temperature increase (running)

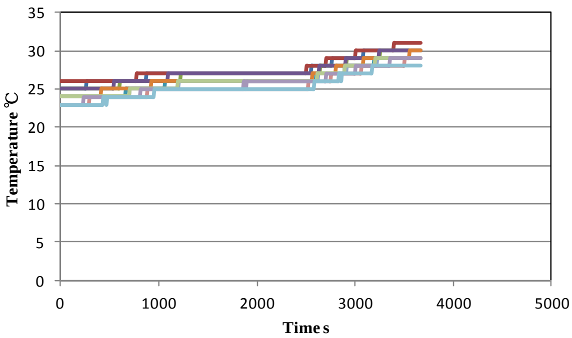
Test No.	A/C	RUNNING			
		Temperature ℃			Time s
		Start	End	ΔT	
1	OFF	16	20	4	2885
2	OFF	24	26	2	2229

Table 8: Battery temperature increase (charging)

Test No.	A/C	IPS CHARGING			
		Temperature ℃			Time s
		Start	End	ΔT	
1	OFF	20	24	4	1155
2	OFF	26	30	4	1152



a) Test No.1



b) Test No.2

Figure 18 Battery Temperature Rising Test

5. Conclusions

1. The Nara and Yukarigaoka tests demonstrated that a short charge was sufficient to recover 70% SOC after a considerably longer period of driving. 7 minutes of charging was sufficient for 5.5km and 30 minutes of running in the Nara test. This demonstrates the feasibility of continuous operation of a short range, rapid charging bus.
2. The tests all showed continuous increases in battery temperature during both running and charging. Temperatures did not reach unacceptably high levels at any point, but it was recognized that active cooling may be necessary for extended use.
3. All three tests showed effective CO_2 emissions rates considerably lower than the equivalent diesel bus. Emissions rates of 0.118 kg-CO_2/km (in Yukarigaoka), 0.120 kg-CO_2/km (in Nara) and 0.189 kg-CO_2/km (in Oze) were achieved with air conditioning switched off, compared with a rate of 0.370 kg-CO_2/km for the diesel bus on the less demanding M15 mode, confirming a significant improvement in environmental performance.
4. Switching on air conditioning at full power was found to have a significant effect on mileage, and almost doubled the rate of CO_2 emissions.

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Authors

Thomas Pontefract
Waseda University, 55S-704, 3-4-1 Ohkubo, Shinjuku Tokyo, JAPAN
Tel:+81-3-5286-3123
Fax:+81-3-5286-3123
Email: tspontefract@asagi.waseda.jp
T. Pontefract received a BSc degree from the University of Leeds, and is currently studying for an M. Eng degree at Waseda University.

Kimiyoshi Kobayashi
Waseda University, 55S-704, 3-4-1 Ohkubo, Shinjuku Tokyo, JAPAN
Tel:+81-3-5286-3123
Fax:+81-3-5286-3123
Email: kimi440gi@moegi.waseda.jp
K. Kobayashi received B.Eng. and M. Eng. degrees, and is currently studying for a D. Eng., at Waseda University.

Kazuaki Seki
Waseda University, 55S-704, 3-4-1 Ohkubo, Shinjuku Tokyo, JAPAN
Tel:+81-3-5286-3123
Fax:+81-3-5286-3123
Email: k.seki@ruri.waseda.jp
K. Seki received a B.Eng., and is currently studying for an M.Eng., at Waseda University.

Yushi Kamiya
Waseda University, 55S-704, 3-4-1 Ohkubo, Shinjuku Tokyo, JAPAN
Tel:+81-3-5286-3123
Fax:+81-3-5286-3123
Email:kamiya@waseda.jp
Y. Kamiya obtained B.Eng. and M.Eng. degrees and received a doctorate of engineering from Waseda University, where he is currently professor.

Yasuhiro Daisho
Waseda University, 58-226, 3-4-1 Ohkubo, Shinjuku Tokyo, JAPAN
Tel:+81-3-5286-3253
Fax:+81-3-5272-3364
Email:daisho@waseda.jp
Y. Daisho graduated the doctor’s course at Waseda University. He is presently professor at Waseda University.

Yu Saito
Waseda Research Institute Corporation, 4F,Waseda Ekimae Building, 5 Babashita-cho, Shinjuku, Tokyo, JAPAN
Tel: +81-3-3208-0102
Fax: +81-3-5272-6195
Email: y.saito7@kurenai.waseda.jp
Y. Saito received the M.Agr. degree from Meiji University. He is Assistant Coordinator at Waseda Research Institute Corporation.

Shunsuke Takahashi
Showa Aircraft Industry CO., Ltd., 600 Tanaka, Akishima, Tokyo, JAPAN
Tel: +81-42-541-2111
Fax: +81-42-541-2111
S. Takahashi received B. and M.Eng. degrees from Waseda University. He is Executive Officer at Showa Aircraft Industry Co., Ltd.