Feasibility Study on In-motion Wireless Power Transfer System Before Traffic Lights Section

Dasiuke Gunji
Powertrain Tech. Dev. Dept.
NSK Ltd.
Fujisawa, Japan
gunji-d@nsk.com

Katsuhiro Hata
Dept. of Electrical Engineering & Information Systems
Graduate School of Engineering,
The University of Tokyo
Tokyo, Japan
hata.katsuhiro13@ae.k.u-tokyo.ac.jp

Osamu Shimizu
Dept. of Advanced Energy
Graduate School of Frontier Science,
The University of Tokyo
Kashiwa, Japan
shimizu.osamu@edu.k.u-tokyo.ac.jp

Takehiro Imura
Dept. of Electrical Engineering & Information Systems
Graduate School of Engineering,
The University of Tokyo
Tokyo, Japan
imura@edu.k.u-tokyo.ac.jp

Hiroshi Fujimoto
Dept. of Advanced Energy
Graduate School of Frontier Science,
The University of Tokyo
Kashiwa, Japan
fujimoto@k.u-tokyo.ac.jp

***Abstract*— In order to improve usability of Electric vehicles (EVs), in-motion Wireless Power Transfer (WPT) technology is one of a game changing solution. In order to maximize the benefit of an in-motion WPT system, it is necessary to find the optimal installation location. In the previous study, the authors found that 30 m length section before traffic lights is the best location by analyzing actual driving data on urban public roads in Japan. In this study, the authors have carried out feasibility study on implementation of in-motion WPT system. Transmit power and efficiency of a virtual in-motion WPT system are simulated.**

Keywords—Electric vehicles, In-motion wireless power transfer

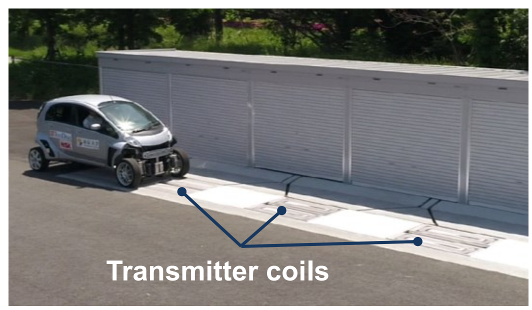


Fig. 1 In-motion Wireless Power Transfer system

I. Introduction

Electrification is one of a big trend of automotive industry field to achieve low-carbon society. Battery Electric Vehicles (BEVs) has been already commercialized. However, the sales volume of the BEVs is still limited because of short mileage per charge and long charging time. In order to solve these issues, in-motion power transfer (also called "Dynamic charging") technology is one of a solution. The advantages of the in-motion power transfer are follows:

1. Reducing on-board battery capacity
2. Reducing vehicle weight and energy consumption
3. Users does not have to worry about charging time
4. Possibility of using in-motion EV battery as buffer of electric power grid

Therefore, in-motion power transfer is one of a key technology to realize low-carbon society.

In order to realize in-motion power transfer, contact type[1] and wireless type[2][3] system have been studied. The authors research group have developed in-motion WPT system via magnetic resonance coupling as shown in Fig. 1[4].

Large-scale investment is necessary to introduce in-motion WPT system on public roads. Therefore, its economic feasibility must be carefully studied. In order to quantitatively simulate the benefit of in-motion WPT system, some simulation study have been carried out in highway case[5] and urban roads case[6] using standard driving cycles. However, standard driving cycles are insufficient to simulate actual driving condition. Therefore, the authors have carried out driving data analysis and found that 30 m length section before traffic light is the best location to install in-motion WPT system because cars exists relatively high frequency on that section. As a result of analysis, assumed necessary performance of in-motion WPT system are 14.7kW transmit power, 85 % efficiency to realize zero net output energy from on-board battery on passenger vehicle case.

In this study, the authors investigated the implementation of the system from the viewpoint of feasibility of the above required performance by simulation using coil specifications of the developed in-motion WPT system.

The structure of this paper is as follows: In the section 2, outlines of the analysis results of actual driving data on our previous study is briefly described. In the section 3, coil characteristics of the developed in-motion WPT system is described. In the section 4, the authors simulate the performance of a virtual in-motion WPT system with 30 m section length, and discuss whether the target performance defined by the analysis results in the section 2 is feasible. Finally, the summary and future issues are described in the section 5.

II. Driving Data Analysis on Urban Roads

In this section, the authors outline the analysis results of driving data in our previous study. For details, please refer to the paper [7].

On the previous study, the authors have collected and analyzed more than 200 km driving data on urban public road in Kanagawa area in Japan. Driving data consists of vehicle velocity, latitude, longitude, and longitudinal acceleration. Straight distance from every measured data point to the closest stop line before traffic lights was calculated. Finally, frequency of existence histogram and cumulative frequency of existence was derived.

Figure 2 shows the analysis result. According to the result, the authors found that the vehicle stayed about 25% of the total traveled time in the 30 m length section before the stop line with traffic light. Therefore, the authors concluded that before traffic lights is the best location to install in-motion WPT system.

By using the calculated cumulative frequency of existence data, it is possible to estimate necessary transmit power of the WPT system to achieve net zero output energy from on-board battery as following equation:

$$P_{send} = \frac{V_{ave} E_C}{\eta \; CFE} \quad [\text{kW}] \qquad (1)$$

where V_{ave} [km/h] is the average vehicle velocity include stoppage time, E_c [kWh/km] is the assumed electrical mileage of EVs, η[-] is the overall efficiency of the in-motion WPT system, and CFE [-] is the cumulative frequency of existence as shown in Fig. 2. Figure 3 shows example of a calculation result. Calculation parameters are V_{ave} = 21.6 km/h, E_c = 0.14 kWh/km, η = 0.85, and CFE value is shown in Fig. 2. According to Fig. 3, if the in-motion WPT section length is 30 m, necessary transmit power is 14.7 kW. Then, necessary received power on the vehicle is 14.7 × 0.85 = 12.5 kW.

On the above calculation, it is assumed that transmit power and efficiency is always constant in the WPT section. However, on actual implementation, they change with relative position between the road coil and the receiver coil. Therefore, in the actual implementation, it is necessary to achieve the above-mentioned target performance as an average over the entire in-motion WPT section.

As an actual driving scene, a vehicle may stop by a red traffic light in in-motion WPT section. At this time, depending on the vehicle stop position, power may not supply to a vehicle if the stop position is not controlled. However, such a situation is considered to be avoidable in combination with the autonomous driving technology. Therefore, in this research, the authors only focus the average performance within the WPT section.

III. Wireless in-Motion Charging System

A. System configuration

The authors research group has developed in-motion WPT system via magnetic resonance coupling as shown in Fig. 1[4]. The road side (transmitter side) facility consists of inverters and road coils. Road coils are arranged on the road at constant intervals. One road coil is operated by one inverter. Vehicle side (receiver side) equipment is integrated in the in-wheel motor. Vehicle side equipment consists of a receiver coil and a converter. The output of the converter is connected to lithium-ion capacitor via DC/DC converter and an inverter which operates e-machine. All these circuit is integrated on the in-wheel motor.

The system employs Series-Series (SS) compensation topology. In the SS topology, a large current flows if the transmitter coil is operated with no receiver coil. In order to avoid that, it is necessary to control start and stop of power transfer by detecting the approach of the receiver coil. The authors have developed a method to detect receiver coil from the current variation of the transmitter coil [8]. By using this method, it can be considered that WPT is performed when the coupling factor between a transmitter coil and a receiver coil is equal to or greater than a predetermined threshold.

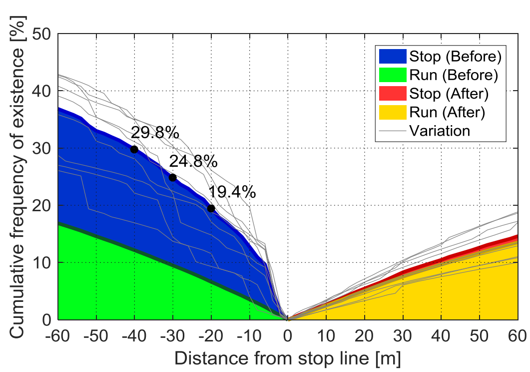


Fig.2. Analysis result of driving data on public roads in Japan [7]

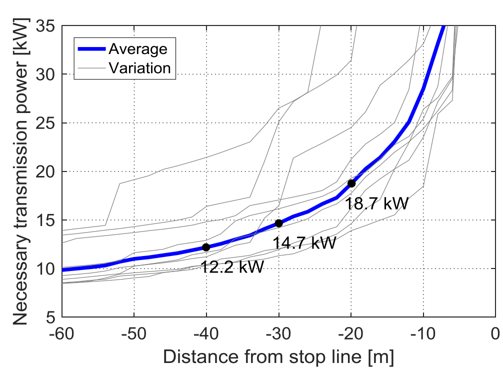


Fig.3. Rough estimation result of the necessary transmit power of in-motion WPT system [7]

In many other previous researches, it is common to install a receiving coil on the bottom of the vehicle and received power is supplied to the on-board battery. On the other hand, the system developed by the authors is different in that the received power is directly supplied to the in-wheel motor. Please refer to the paper [4] for details. However, since the main purpose of this research is to study the performance of the in-motion WPT system. Then, in this study, only the values of the coil characteristics of the development system were used.

B. Coil characteristics measurement

Characteristics of the coils are listed in Table.1. Winding area of the road coil is about 1.3 m × 0.4 m. Winding area of the receiver coil is about 0.3 m × 0.25 m. Ferrite plates are placed behind each coils to increase magnetic coupling.

The authors have measured coupling factor map between the road (transmitter) coil and the receiver coil as shown in Fig. 4. Vertical gap between coils was 0.1 m. Measurements were taken in one quadrant on the road coil and the coupling factor map was obtained assuming that the other quadrants were symmetric. Center position of the receiver coil was changed every 0.05 m from zero to 0.9 m in longitudinal direction and every 0.025 m from zero to 0.3 m in lateral direction. For example, the measurement point (0, 0) is the position where the center of the road coil and the center of the receiver coil coincide. Linear interpolation was made between measurement points.

The obtained coupling factor map is shown in Fig.5. The dotted line in the figure is the winding area of the road coil.

TABLE I. COIL SPECIFICATIONS

Road coil (Transmitter)	Inductance L_1	429.0 μH
	Resistance R_1	342.5 mΩ
	Q factor Q_1	669.0 @85kHz
Receiver coil	Inductance L_2	377.7μH
	Resistance R_2	383.3 mΩ
	Q factor Q_2	526.3 @85kHz

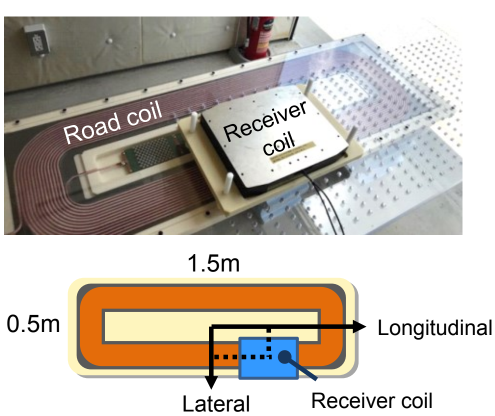


Fig. 4. Coupling factor measurement setup

Figure 6 shows coupling factor variation in longitudinal direction in two different lateral misalignment cases. It can be seen that a coupling factor of 0.08 or more is obtained in a wide area. On the other hand, it also can be seen that the coupling factor changes rapidly in a short distance near the road coil edge.

IV. SIMULATION

A. Transmit power and efficiency calculation

In this section, performance simulation of a virtual in-motion WPT system is described. If the resonance condition is satisfied and only focus on the fundamental wave component, transmit power P_1, received power P_2, and efficiency between coils η are calculated as follows:

$$P_1 = V_{11}I_{11} = V_{11}\frac{R_2V_{11} + \omega_0 L_m V_{21}}{R_1R_2 + (\omega_0 L_m)^2} \quad (2)$$

$$P_2 = V_{21}I_{21} = V_{21}\frac{\omega_0 L_m V_{11} - R_1 V_{21}}{R_1R_2 + (\omega_0 L_m)^2} \quad (3)$$

$$\eta = \frac{P_2}{P_1} \quad (4)$$

$$L_m = k\sqrt{L_1 L_2} \quad (5)$$

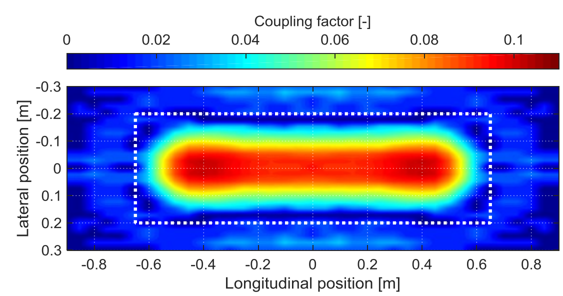


Fig. 5. Coupling factor map

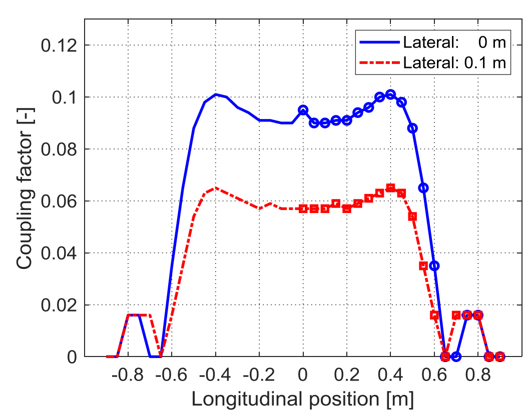


Fig. 6. Coupling factor variation in longitudinal direction

where V_{11} [Vrms] is fundamental component of transmitter inverter output voltage (hereinafter called transmitter side voltage), V_{21} [Vrms] is fundamental component of receiver converter (or rectifier) input voltage (hereinafter called receiver side voltage), and ω_0 [rad/s] is resonance angular frequency. On the calculation, operating frequency was set to 85 kHz. Self-inductance variation of the coils due to the relative position variation is not considered.

As described above, in the SS topology, it is necessary to start power transmission after detecting the presence of a receiver coil. In the simulation, this is simplified as power transfer is performed only when the coupling factor exceeds a certain threshold value. In the simulation, the time taken for detection and the transient response of the coil current are ignored.

B. Device performance constraints

Now, we focus on the transmit power when the coupling factor between coils is low. This corresponds to the situation where the receiver coil enters or advances to the road coil. Figure 7 shows the calculated values of the transmitter side current and receiver side current with respect to the coupling factor when the transmitter side voltage and the receiver side voltage are fixed at 550 Vrms. From Fig. 7, when the both side voltage are constant, it can be seen that a large current flows in each coil when the coupling factor is low. In an actual equipment, since there are constraints on the maximum current and voltage depending on the performance of the switching device and the resonant capacitor, constant voltage operation is impossible. Therefore, it is necessary to control the transmitter side voltage and the receiver side voltage to satisfy the current constraints.

As it is clear from equation (2) and (3), both the transmitter side current and the receiver side current are affected by both the transmitter side voltage and the receiver side voltage. However, it is not appropriate to control both sides cooperatively using signal communication between both sides because of communication delay. Therefore, it is desirable that the transmitter side and the receiver side are independently controlled. The implementation of such control system is for further study. In this research, the combination of the transmitter side voltage and the receiver side voltage that maximizes the transmission power while satisfying the current constraint is obtained by round robin calculation.

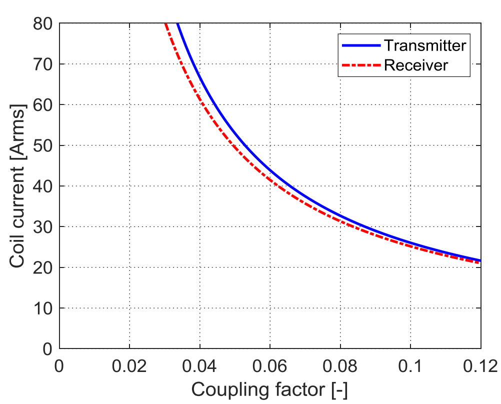
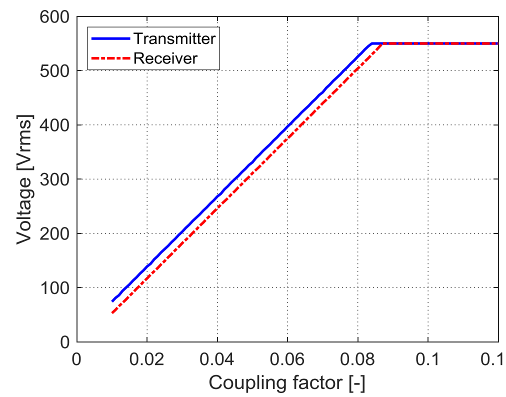


Fig. 7. Coupling factor vs. coil current

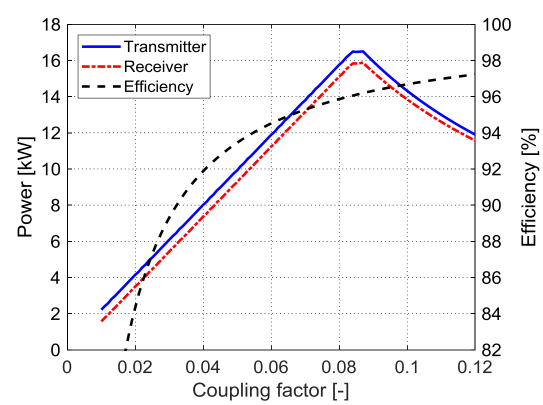
Figure 8 shows optimized transmitter side and receiver side operation voltage, transmit power, and efficiency when current constraint is 30 Arms and voltage constraint is 550 Vrms. If operation voltage was fixed to 550 Vrms, coupling factor threshold value must be 0.08 or more to satisfy current constraint. That means, available operation area becomes smaller. Therefore, voltage control on low coupling factor condition is necessary to maximize transmit energy.

C. Performace calculation on single coil

Transmit power, received power, and efficiency on one road coil were calculated using equation (2) to (4). The voltage constraints was 550 Vrms and the current constraint was 30 Arms both on the transmitter side and the receiver sides, It was assumed that each side voltage was optimally controlled and the control response time was neglected. The threshold value of the coupling factor for starting and ending power transfer was 0.025. The efficiency of the receiver side converter was assumed to be 97%.



(a) Optimized operation voltage



(b) Power and efficiency

Fig. 8. Optimized operation condition considering current constraints

Figure 9 shows the calculation result. According to the calculation results, when the coupling coefficient is 0.087, the maximum transmit power is 16.5 kW, the efficiency is 93.3% including receiver side converter efficiency, and the received power is 15.4 kW. The authors have conducted power transfer experiment in the stationary state using the same coil, and obtained 92.3% of efficiency including the efficiency of both the transmitter side inverter and the receiver side converter at 12.5 kW transmit power [4]. Therefore, the authors concluded that the calculation results are adequate.

D. Simulation of a virtual in-motion WPT system

Finally, performance simulation of a virtual in-motion WPT system have been carried out. The configuration of the virtual system is shown in Fig. 10. The characteristic values of each coil are shown in Table 1 and Fig. 5. The configuration of the virtual system are follows:

A) On the road side, 12 road coils are installed at equal intervals 30 m before the stop line of the traffic light.

B) Unlike the existing developed system shown in Fig. 1, the road coils are installed only in one row at the center of the road.

C) Two receiver coils are installed on the bottom of the vehicle at an interval in the longitudinal direction.

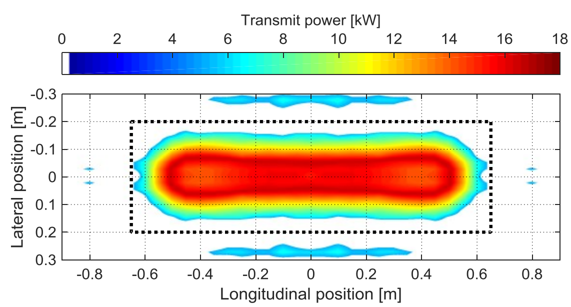
D) The coil intervals ware set so that power is transmitted from only one road coil to only one receiver coil.

E) The received power of each receiver coil is respectively rectified by the converter and charged to the on-board battery through the DC/DC converter.

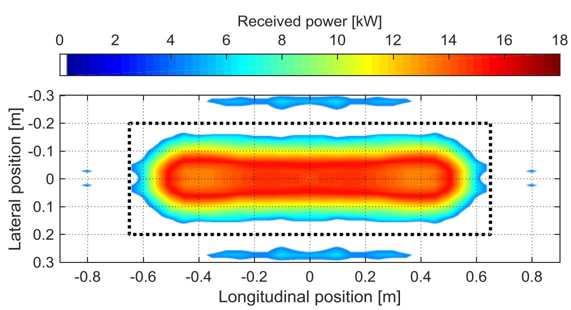
F) The transmitter side inverter and the receiver side converter are ideally controlled to satisfy current and voltage constraints respectively.

G) The maximum voltage constraint was set to 550 Vrms, and the maximum current constraint was set to 30 Arms. Note that this current constraint value is larger than our developed system.

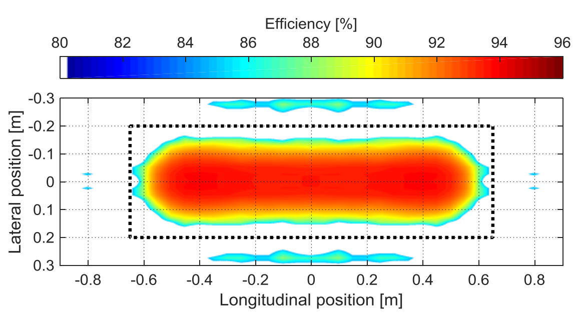
Figure 11 shows the simulation results on zero lateral misalignment. Table 2 shows the average received power and average efficiency on the vehicle (that is, the sum of the two receiver coils) in the in-motion WPT section in the case of zero and 0.1 m lateral misalignment respectively. When the lateral misalignment was zero, the average received power was 12.2 kW, which is slightly lower than the target. When the lateral



(a) Transmit power

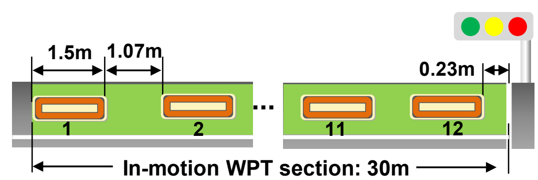


(b) Received power

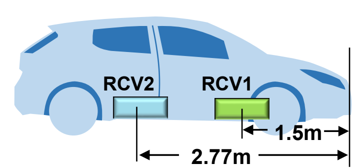


(c) Efficiency (include receiver side converter efficiency)

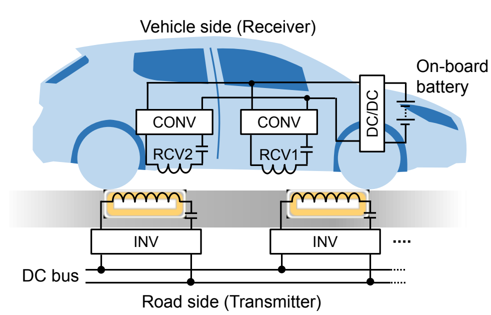
Fig. 9. Calculation results



(a) Coil arrangement on road side

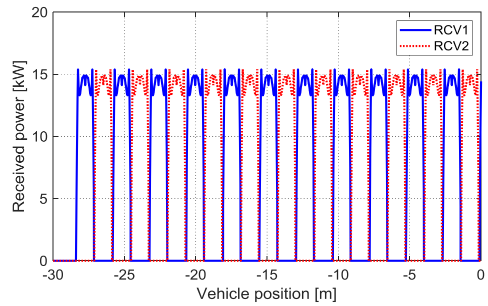


(b) Coil arrangement on vehicle side

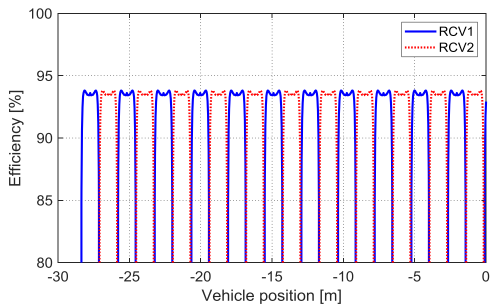


(c) Circuit configuration

Fig. 10. Configuration of the virtual in-motion WPT system



(a) Received power



(b) Efficiency

Fig. 11. Simulation results (Zero lateral displacement)

misalignment was 0.1 m, the average received power was 8.7 kW, which is significantly short of the target value. On the other hand, focusing on the efficiency, it was 91.2% on average even at a 0.1 m lateral misalignment. From the above simulation results, the authors concluded that the target performance can be realized by increasing the voltage and current capacity on both the transmitter side and the receiver side.

V. Conclusion

In the previous study, the authors estimated the target performance of an in-motion WPT system on urban road using actual driving data. As a result, the authors concluded that the necessary in-motion WPT section length was 30 m before traffic signal, and the average received power was 12.5 kW. In this paper, the authors have performed simulation using the coil characteristic values of our developed system, and concluded that the above target performance value is feasible.

In order to realize the target performance, it is necessary to improve the performance of component parts, such as increasing the current capacity of the switching element and increasing the voltage capacity of the resonant capacitor. Furthermore, it is important issue that the establishment of control methods of both side current at low coupling factor condition. In addition, it is necessary to discuss scenarios for spreading the system and the economic feasibility.

TABLE II. Simulation Results

	Target (constant)	Simulation (average)	
		y = 0 m	y = 0.1 m
Transmit power	14.7 kW	13.1 kW	9.6 kW
Efficiency	85 %	93.1 %	91.2 %
Received power	12.5 kW	12.2 kW	8.7 kW

y: lateral misalignment

Acknowledgment

This work was partly supported by JST-Mirai Program (JP-MJMI17EM), Japan and Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), "Energy system toward a decarbonized society" (Founding agency: JST).

References

[1] T. Tajima, W. Noguchi, and T. Aruga, "Study of a Dynamic Charging System for Achievement of Unlimited Cruising Range in EV", SAE Technical Paper, 2015-01-1686, 2015

[2] J. M. Miller, P. T. Jones, J-M. Li, and O. C. Onar, "ORNL Experience and Challenges Facing Dynamic Wireless Power Charging of EV's", IEEE Circuits and Systems Magazine, vol. 15, Issue 2, pp. 40–53, 2015

[3] N. Sakai, D. Itokazu, Y. Suzuki, S. Sakihara, and T. Ohira, "One-kilowatt capacitive Power Transfer via wheels of a compact Electric Vehicle", Proc. 2016 IEEE Wireless Power Transfer Conference, pp. 1–3, 2016

[4] H. Fujimoto, T. Takeuchi, K. Hanajiri, K. Hata, T. Imura, M. Sato, D. Gunji, and G. Guidi, "Development of Second Generation Wireless In-Wheel Motor with Dynamic Wireless Power Transfer", , Proc. EVS31 and EVTeC2018, pp.1–7, 2018

[5] S. Chopra and P. Bauer, "Driving Range Extension of EV With On-Road Contactless Power Transfer–A Case Study", IEEE Trans. IE, vol. 60, no. 1, pp. 329–338, 2013

[6] L. Patnaik, P. S. Huynh, D. Vincent, and S. S. Williamson, "Wireless Opportunity Charging as an Enabling Technology for EV Battery Size Reduction and Range Extension: Analysis of an Urban Drive Cycle Scenario", Proc. 2018 IEEE PELS Wow, pp.1-5, 2018

[7] D. Gunji, Y. Mukai, T. Imura, and H. Fujimoto, "Basic Study on Arrangement Design of In-motion Charging Facility on Urban Roads", Proc. IEEE IECON2018, pp. 5153-5158, 2018

[8] K. Hata, K. Hanajiri, T. Imura, H. Fujimoto, Y. Hori, M. Sato, and D. Gunji, "Design and Implementation of Sensorless Vehicle Detection System for In-motion Wireless Power Transfer", Proc. EVS31 and EVTeC2018, pp.1-7, 2018