Feasibility Study for Dynamic Wireless Power Transfer in Simulation with Big Data Focusing on Battery Capacity Requirement of Electric Vehicles

1st Kota Fujimoto
The University of Tokyo
Chiba, Japan
fujimoto.kota21@ae.k.u-tokyo.ac.jp

2nd Osamu Shimizu
The University of Tokyo
Chiba, Japan
shimizu.osamu@edu.k.u-tokyo.ac.jp

3rd Hiroshi Fujimoto
The University of Tokyo
Chiba, Japan
fujimoto@k.u-tokyo.ac.jp

4th Shuji Kawano
Honda R&D Co., Ltd.
Tochigi, Japan
shuji_kawano@jp.honda

5th Jin Katsuya
Honda R&D Co., Ltd.
Tochigi, Japan
jin_katsuya@jp.honda

6th Tetsu Sato
Honda R&D Co., Ltd.
Tochigi, Japan
tetsu_sato@jp.honda

***Abstract*—Dynamic Wireless Power Transfer (DWPT) has been proposed to solve the problems of electric vehicles. The requirements of DWPT are changed by not only the specifications of vehicles, but also the driving style of each driver. This paper presents the battery capacity requirements of DWPT by analyzing big data obtained by customers' vehicles. The proposed analysis method shows $99\,\%$ of vehicles can drive infinitely if they have at least $7.88\,\mathrm{kWh}$ battery when the output of the in-motion charging is set to $P_{\mathrm{in,WPT}} = 40\,\mathrm{kW}$.**

***Index Terms*—electric vehicles, dynamic wireless power transfer, requirement analysis, big data, simulation**

I. Introduction

Electric vehicles (EVs), which do not emit greenhouse gases while driving, are being promoted to make the transportation society sustainable. On the other hand, the EVs are facing the following issues: greenhouse gas (GHG) emissions during vehicle manufacturing and energizing, and short cruising range because of the dependency on the battery as power supply. Increasing the amount of batteries installed in the vehicle is effective in extending the cruising range. However, it also increases the GHG emissions associated with battery production. In addition, the increase in vehicle weight increases driving resistance, which in turn increases the energy required for driving. As the energy required for driving increases, the amount of electricity to recharge EVs also increases. In many countries, fossil fuels are used to generate electricity, which also increases GHG emissions during power generation.

As a radical solution to these problems, wireless power transfer technology [1]–[7] has been recently applied to vehicles in motion. This technology is called dynamic wireless power transfer (DWPT) [8]–[12]. An overview of the system is shown in Fig. 1. DWPT eliminates the need to store large amounts of electricity in EVs, greatly reducing the amount of batteries installed in the vehicle [13]. Therefore, it is expected to reduce GHG emissions from battery production

Fig. 1. Image diagram of DWPT system.

Fig. 2. Demonstration vehicle for DWPT utilized in Kashiwa, Japan.

[14]. Furthermore, by reducing the number of batteries installed in the vehicle, the energy required for driving can also be reduced [15]. Demonstrations of the DWPT system are being conducted in various locations. For instance, a vehicle as shown in Fig. 2 is utilized in Kashiwa, Japan. It is possible to send $50\,\mathrm{kW}$ energy from the transfer coils set at an intersection.

In previous studies, the effect of implementing DWPT is described based on the energy consumption calculated from vehicle data of speed, road gradient, and other information

[13]. However, these studies just calculate the vehicle motion based on data, and do not include actual factors such as variation of drive resistance, resulting in errors with the practical vehicle output. In addition, the small number of data does not allow for sufficient verification of the proposed estimation because the driver's driving style is varied in each. [16] analyzes historical traffic flow data to examine an EV traffic flow, which aims to reveal the feasibility of the DWPT roads; however it does not focus on the battery capacity requirement of each vehicle.

Although important contributions have been made to the feasibility of DWPT system, the battery capacity requirements of EVs with DWPT based on the big data have not been fully analyzed. Therefore, the goal of this research is set to calculate the required battery capacity with DWPT system by analyzing big data obtained from commercially available vehicles.

Section Ⅱ describes the big data handled in this study. In section Ⅲ, the data analysis methods are described. In section Ⅳ the results of the data analysis are shown, and section V summarizes the paper.

II. Big data information

The big data utilized in this paper is registered in the database based on the data sampled at small hybrid vehicles that seat five passengers according to the standard driving cycle. The data is collected only while the vehicle is powered on.

The structure of the big data is shown in Fig. 3. The data is obtained in Japan; especially we selected the data of the vehicles that drive in Kashiwa at least once because the ongoing feasibility studies are conducted in the city as shown in Fig. 2. The data was obtained over half a year from December 1st, 2022 to May 31st, 2023, and consists of a table with approximately 5.33 billion rows. The sampling period of data acquisition is three seconds.

The data type used for analysis is shown in Table. I. The types of roads on which vehicles are traveling are labeled as non-road (including parking lots), expressways, ferry routes, and the other roads are labeled as general roads. In this study, the data of vehicles driving along general roads is considered.

III. Required battery capacity analysis with big data

In this section, the energy analysis method is introduced. The total energy utilized in a vehicle with DWPT ($E_{\text{total}}(t)$) is defined as the difference between the energy consumed by driving ($E_{\text{drive}}(t)$) and the energy supplied by DWPT ($E_{\text{WPT}}(t)$). In the below subsections, the detailed definition of each parameter is described.

A. Consumption energy in driving $E_{\text{drive}}(t)$

The energy consumed by driving $E_{\text{drive}}(t)$ is shown as

$$E_{\text{drive}}(t) = \int_0^t P_{\text{out,drive}}(t)dt, \tag{1}$$

$$P_{\text{out,drive}} = \frac{T_{\text{shft}}}{r_{\text{tire}}} \cdot V_{\text{p}} \cdot \frac{1}{\eta_{\text{torque}}}, \tag{2}$$

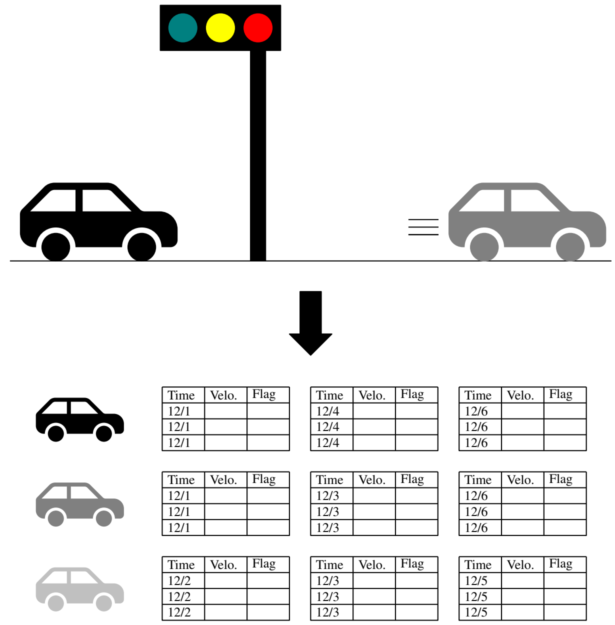

Fig. 3. Image diagram of data table created by sampled data on each vehicle

TABLE I
DATA TYPE FOR ANALYSIS

Symbol	Parameter	Unit
ID_{v}	Vehicle ID	-
t_{check}	Check time	-
V_{p}	Vehicle speed	m/s
T_{shft}	Drive shaft torque	N s
r_{tire}	Tire radius	m
η_{torque}	Torque transmission efficiency	-
θ_{brk}	Brake opening position	%
ID_{road}	Road ID	-

where $P_{\text{out,drive}}$ is the output of vehicle, T_{shft} is the drive shaft torque, V_{p} is the vehicle speed, r_{tire} is the tire radius of the vehicle, and η_{torque} is the torque transmission efficiency from motor torque or engine torque to the drive shaft output torque.

B. Supplied energy from DWPT $E_{\text{WPT}}(t)$

Since previous studies have shown that vehicles frequently run or stop around the intersections [13], it is decided to analyze the data by assuming that the time available for power supply is the same with the time the vehicle are located at the intersection. However, since the location information of the intersection is not included in the database, this study considers the following three conditions occurring simultaneously as stopping time at the intersection.

1) Vehicle speed $V_{\text{p}} = 0\,\text{m/s}$
2) Brake opening position $\theta_{\text{brk}} > 0\,\%$
3) Road IDs ID_{road} are general roads

TABLE II
SIMULATION PARAMETERS.

Parameter	Value
Tire radius r_{tire}	$0.293\,\mathrm{m}$
Torque transfer efficiency η_{torque}	0.894
Average Transfer Power $P_{\mathrm{in,WPT}}$	$25\,\mathrm{kW}$

In real situations, it is possible to take into account the time running in intersections for power supply, but in this study, only the stopping conditions are considered as the time available for wireless power transfer.

Based on the above, the wireless power transfer energy E_{WPT} is defined as

$$E_{\mathrm{WPT}}\left(t\right)=\int_{0}^{t}f_{\mathrm{stop}}\left(t\right)P_{\mathrm{in,WPT}}(t)dt, \tag{3}$$

where $f_{\mathrm{stop}}\left(t\right)$ is the intersection flag indicating that the data sampling point is a DWPT section, and is a function that outputs one if all the above conditions are met and zero for otherwise. $P_{\mathrm{in,WPT}}(t)$ is the receiving power at vehicles. In this study, this value is considered as the average transferred power for the simple implementation.

C. Total energy consumption in vehicles $E_{\mathrm{total}}\left(t\right)$

The definition of total energy consumed by the vehicle $E_{\mathrm{total}}\left(t\right)$ is described as below.

$$E_{\mathrm{total}}\left(t\right)=E_{\mathrm{drive}}\left(t\right)-E_{\mathrm{WPT}}\left(t\right), \tag{4}$$

$E_{\mathrm{total}}\left(t\right)$ is defined as $0\,\mathrm{kWh}$ at the starting point of data for each vehicle. Also, each vehicle is assumed to be fully charged at the starting point. Thus, $E_{\mathrm{total}}\left(t\right)=0$ means fully charged. In addition, $E_{\mathrm{total}}\left(t\right)$ is never be less than zero, because power control is performed at either the transmission side or the receiving side to shut off the power supply to the battery. Furthermore, it is assumed that EVs are charged only by DWPT in this study. That is, the battery capacity is maintained at a constant level during the rest time.

Defining the maximum value in timeseries of $E_{\mathrm{total}}\left(t\right)$ as $E_{\mathrm{total,max}}$ and the minimum value as $E_{\mathrm{total,min}}$, the difference $\Delta E=E_{\mathrm{total,max}}-E_{\mathrm{total,min}}$ is calculated as the required battery capacity. This is the target factor in this study.

D. excluded data

The purpose of this study is to derive the battery capacity required when DWPT system is sufficiently installed on a public road, meaning intersections exist at regular intervals while driving. To satisfy this assumption, the following data, which do not fit this assumption, are excluded from the analysis.

1) Data for one driving whose ratio of intersection stop time to total time is less than 0.1 or more than 0.9

The reason for excluding cases where the ratio of intersection stop time to total time is less than 0.1 is that intersection stop time is unlikely to be extremely small, less than 0.1, when traveling on a public road with intersections. However, in the actual data, there are many cases where the intersection stop time is almost zero. It seems to be because the data for high-speed driving are included in the analysis data due to mistakes in the road ID information.

The reason for excluding cases where the ratio of intersection stop time to the total time is more than 0.9 is as follows: it is unlikely that the vehicles would continue to stop for such a long period on general roads. It seems to be because the actual data often have a short measurement time: for instance, only a short period of startup is conducted.

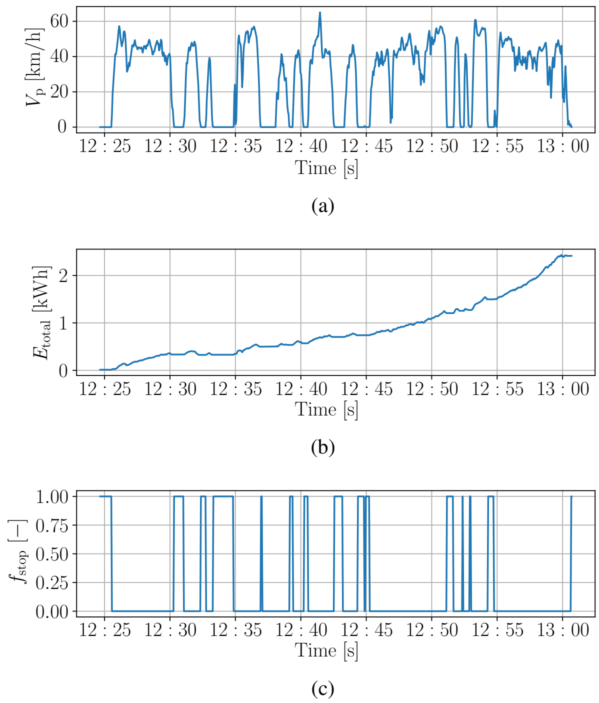

Fig. 4. One example of vehicle data plot when $P_{\mathrm{in,WPT}}=0\,\mathrm{kW}$ (a) Velocity V_{p} (b) Energy E_{total} (c) Flag of intersection f_{stop}

IV. SIMULATION RESULT

This section describes the analysis results in the simulation with big data for The required battery capacity ΔE. As mentioned in section III, the required battery capacity ΔE is obtained as the difference between the maximum and minimum values in the time series data of total energy consumption $E_{\mathrm{total}}\left(t\right)$ obtained in the simulation. By calculating ΔE for each vehicle data and extracting the maximum value ΔE_{max} from each ΔE, it is possible to determine the required battery capacity for EVs with DWPT that take into account various driving conditions. Simulation parameters are shown in Table. II.

A. Analysis of individual data

In this section, the relationship among the particularly important time series of the velocity V_{p}, total energy consumption E_{total}, and intersection flag f_{stop} is explained. As an example,

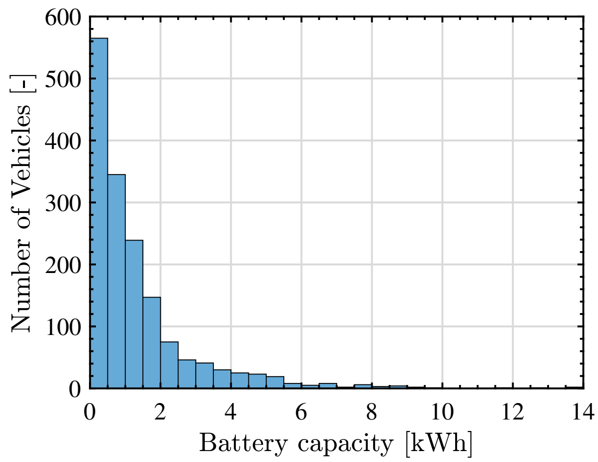

Fig. 5. Number of vehicles for each amount of required battery capacity.

we present the time series data for the case where the DWPT output $P_{\mathrm{in,WPT}} = 0\,\mathrm{kW}$.

The time series data for a specific vehicle when $P_{\mathrm{in,WPT}} = 0\,\mathrm{kW}$ is shown in Fig. 4. First, regarding the relationship between V_{p} and E_{total} as shown in Fig. 4(a) and Fig. 4(b), when V_{p} increases, i.e., during acceleration, E_{total} significantly increases. On the other hand, when V_{p} decreases, i.e., during deceleration, regeneration occurs, and E_{total} significantly decreases. Moreover, when V_{p} is approximately constant, E_{total} increases at a constant rate, making the time series data of E_{total} take a ramp shape. Second, regarding the relationship between E_{total} and f_{stop} as shown in Fig. 4(b) and Fig. 4(c), when $f_{\mathrm{stop}} = 1$, i.e., when the vehicle stops at an intersection, E_{total} becomes constant. Finally, regarding the relationship between V_{p} and f_{stop} as shown in Fig. 4(a) and Fig. 4(c), when $f_{\mathrm{stop}} = 1$, i.e., when the vehicle stops at an intersection, $V_{\mathrm{p}} = 0\,\mathrm{m/s}$. In this way, it is confirmed that the data is correctly sampled.

Regarding the vehicle data when $P_{\mathrm{in,WPT}} > 0\,\mathrm{kW}$, the relationship between V_{p} and E_{total}, as well as between V_{p} and f_{stop}, tends to be the same as when $P_{\mathrm{in,WPT}} = 0\,\mathrm{kW}$. However, the relationship between E_{total} and f_{stop} is differenct. When $f_{\mathrm{stop}} = 1$, i.e., when it is determined that the vehicle is stopping at an intersection, charging occurs, and E_{total} decreases. The slope of the decrease in E_{total} depends on the DWPT receiving power $P_{\mathrm{in,WPT}}$, and the greater the DWPT receiving power $P_{\mathrm{in,WPT}}$, the steeper the decrease in E_{total}, but excessive output will make E_{total} stick to zero.

The required battery capacity ΔE is calculated by obtaining the maximum and minimum values from the time series data of E_{total} and calculating their difference. From the data in Fig. 4, it is possible to calculate $\Delta E = 2.4\,\mathrm{kWh}$ from Fig. 4(b). In the next section, we will calculate ΔE for each vehicle and determine the maximum value ΔE_{max} among the vehicles, thereby deriving the required battery capacity for a certain DWPT receiving power based on big data.

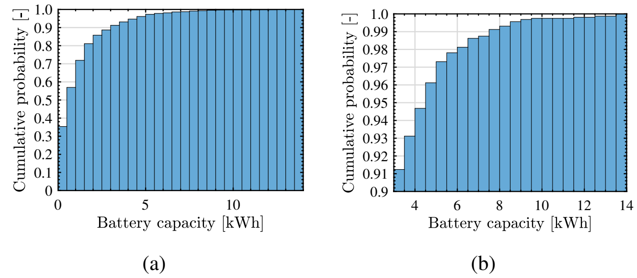

Fig. 6. Cumulative probability. (a) Overview (b) Enlarged view of probability more than 0.9

B. Analysis of overall data

In this study, the maximum required battery capacity ΔE_{max} is examined when setting the average output of the wireless power transfer system $P_{\mathrm{in,WPT}} = 40\,\mathrm{kW}$. The choice of $P_{\mathrm{in,WPT}} = 40\,\mathrm{kW}$ is based on the fact that a DWPT system with an output of $P_{\mathrm{in,WPT}} = 36\,\mathrm{kW}$ already exists [14], and it is considered fully feasible to achieve $P_{\mathrm{in,WPT}} = 40\,\mathrm{kW}$ in practical implementations.

Fig. 5 shows the number of vehicles for each amount of required battery capacity, and Fig. 6 shows the cumulative probability of required battery capacity as shown in Fig. 5. Fig. 6(a) shows the overview of the cumulative probability, and Fig. 6(b) shows the enlarged view of the cumulative probability. Fig. 6(b) shows $90\,\%$ of vehicles can drive infinitely if they have at least $3.28\,\mathrm{kWh}$ battery when the output of the in-motion charging is set to $P_{\mathrm{in,WPT}} = 40\,\mathrm{kW}$. Fig. 6(b) also shows $95\,\%$, $98\,\%$,$99\,\%$ of vehicles can drive forever if they have at least $4.61\,\mathrm{kWh}$, $6.29\,\mathrm{kWh}$, and $7.88\,\mathrm{kWh}$ battery when the output of the in-motion charging is set to $P_{\mathrm{in,WPT}} = 40\,\mathrm{kW}$, respectively. These results show the feasibility of DWPT system because it can decrease the size of the battery drastically to improve GHG emission in the future.

V. Conclusion

In this paper, big data obtained from commercial vehicles are analyzed to identify the requirements for battery capacities. The conclusions obtained from the simulation results are as follows

1) When the average power of DWPT is $40\,\mathrm{kW}$, $99\,\%$ of vehicles can drive infinitely if they load $7.88\,\mathrm{kWh}$ of batteries.

However, this study has some limitations. First, the DWPT receiving power is set as the constant value. This means that the battery charging is always conducted at constant current mode. However, the charging mode is transferred from the constant current mode to the constant voltage mode in the actual system [17], and this point should be considered in future studies. Second, the decrease of the driving resistance is not considered in this study. This means that the required battery capacity might be further decreasing compared to the result in this paper. This point will also be analyzed in future studies.

For further feasibility study of DWPT system, the optimal output power of DWPT system will be examined while considering the battery capacity. In addition, the distribution rate of the DWPT system at intersections was assumed to be $100\,\%$ in this study, but analysis of the required battery capacity when the distribution rate is varied will be also conducted. Finally, this study estimated the stopping conditions at intersections based on the vehicle operating conditions, but in the future, we will conduct the analysis based on the location information of intersections obtained as map data.

Acknowledgment

This work was partly supported by JST-Mirai Program Grant Number JPMJMI21E2 and Council for Science, Technology and Innovation (CSTI), Cross-ministerial Strategic Innovation Promotion Program (SIP), the 3rd period of SIP "Smart energy management system" Grant Number JPJ012207 (Funding agency: JST).

References

[1] T. Campi, S. Cruciani, F. Maradei, and M. Feliziani, "Near-Field Reduction in a Wireless Power Transfer System Using LCC Compensation," *IEEE Trans. Electromagn. Compat.*, vol. 59, no. 2, pp. 686–694, 2017.

[2] E. Moisello, A. Liotta, P. Malcovati, and E. Bonizzoni, "Recent Trends and Challenges in Near-Field Wireless Power Transfer Systems," *IEEE Open Journal of the Solid-State Circuits Society*, vol. 3, pp. 197–213, 2023.

[3] E. Afjei, A. Siadatan, R. Naghash, A. Gholipour, and A. Rezaei-Zare, "Impact of Body Tissue on Induced Electromotive Force in Wireless Power Transfer Coils," in *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 2022.

[4] L. Solimene, F. Corti, S. Musumeci, C. S. Ragusa, and A. Reatti, "Magnetic Control of LCC-S Compensated Wireless Power Transfer System," in *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 2022.

[5] F. Grazian, T. B. Soeiro, and P. Bauer, "Design Trade-Offs Between the Coupled Coils' Inductance and the Series-Series Compensation Capacitance for EV Wireless Charging Systems," in *2022 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM)*, 2022.

[6] K. Kusaka, K. Yamagata, J. Katsuya, and T. Sato, "Reduction in Leakage Magnetic Flux of Wireless Power Transfer Systems with Halbach Coils," *IEEJ Journal of Industry Applications*, vol. 12, no. 6, pp. 1104–1105, 2023.

[7] A. Konishi, K. Umetani, M. Ishihara, and E. Hiraki, "Autonomous Resonant Frequency Tuner for a 6.78MHz Inductive Coupling Wireless Power Transfer System to Stably Maximize Repeater Current," *IEEJ Journal of Industry Applications*, vol. 12, no. 2, pp. 215–227, 2023.

[8] G. A. Covic, J. T. Boys, M. L. G. Kissin, and H. G. Lu, "A Three-Phase Inductive Power Transfer System for Roadway-Powered Vehicles," *IEEE Transactions on Industrial Electronics*, vol. 54, no. 6, pp. 3370–3378, 2007.

[9] J. Shin, S. Shin, Y. Kim, S. Ahn, S. Lee, G. Jung, S.-J. Jeon, and D.-H. Cho, "Design and implementation of shaped Magnetic-Resonance-Based wireless power transfer system for Roadway-Powered moving electric vehicles," *IEEE Transactions on Industrial Electronics*, vol. 61, no. 3, pp. 1179–1192, 2014.

[10] A. Kamineni, M. J. Neath, A. Zaheer, G. A. Covic, and J. T. Boys, "Interoperable EV Detection for Dynamic Wireless Charging With Existing Hardware and Free Resonance," *IEEE Transactions on Transportation Electrification*, vol. 3, no. 2, pp. 370–379, 2017.

[11] T. Imura, K. Sasaki, Y. Yamada, K. Hanawa, and N. Abe, "Study on Dynamic Wireless Power Transfer System on Expressways from the Viewpoint of Economic Feasibility," in *2022 JSAE Annual Congress SPRING*, 2013.

[12] O. Shimizu, T. Fujita, S. Nagai, H. Fujimoto, and Y. Omori, "Development of Dynamic Wireless Power Transfer Coils for 3rd Generation Wireless In-Wheel Motor," *IEEJ Transactions on Industry Applications*, vol. 141, no. 8, pp. 638–645, 2021.

[13] D. Gunji, K. Hata, O. Shimizu, T. Imura, and H. Fujimoto, "Feasibility Study on In-motion Wireless Power Transfer System Before Traffic Lights Section," in *2019 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*, 2019.

[14] O. Shimizu, S. Nagai, T. Fujita, H. Fujimoto, D. Gunji, H. Sumiya, E. Takahashi, N. Yamaguchi, and K. Tani, "Evaluating Reduction of Greenhouse Gas Emission by Magnetic Resonance Coupled Dynamic Wireless Power Transfer of Electric Vehicles Considered with Vehicle Production," *IEEJ Transactions on Industry Applications*, vol. 142, no. 10, pp. 736–743, 2022.

[15] O. Shimizu, S. Nagai, T. Fujita, and H. Fujimoto, "Potential for CO_2 Reduction by Dynamic Wireless Power Transfer for Passenger Vehicles in Japan," *Energies*, vol. 13, no. 13, pp. 1–15, 2020.

[16] T. Newbolt, P. Mandal, H. Wang, and R. Zane, "Sustainability of dynamic wireless power transfer roadway for In-Motion electric vehicle charging," *IEEE Transactions on Transportation Electrification*, vol. 10, no. 1, pp. 1347–1362, Mar. 2024.

[17] C. Gould, K. Colombage, J. Wang, D. Stone, and M. Foster, "A Comparative Study of On-Board Bidirectional Chargers for Electric Vehicles to Support Vehicle-to-Grid Power Transfer," in *2013 IEEE 10th International Conference on Power Electronics and Drive Systems (PEDS)*, 2013.