Verification of Electrical Characteristics by Coils Embedded in Asphalt Pavement and 100,000 Wheel Traveling Test of a Heavy-Duty Vehicle in Dynamic Wireless Power Transfer

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***Abstract*—In dynamic wireless power transfer, the transmitter coils are embedded in the road pavement. The coils must have both electrical characteristics that can supply sufficient power for electric vehicles to run and mechanical strength equal to or greater than that of ordinary road pavement. In this paper, coils were embedded with MMA resin mixture in two different locations on a circular pavement running test site, one at the wheel-to-wheel location assuming operation on an actual road and the other below the wheel running location to compare durability, and the durability and electrical characteristics of the pavement were evaluated before and after a 100,000 wheels (5t wheel load equivalent) running test by a large vehicle. As a result, there was no damage to the pavement or the coils themselves after the driving test, and all coils achieved an output power of 46 kW or more and a transmission efficiency of 81% or more when the input voltage was converted to 600 V using VNA for electrical characteristics. This indicates that the coil mounting method using MMA resin mixture is suitable in terms of both mechanical strength and electrical characteristics.**

***Keywords*— Dynamic wireless power transfer, Embedment coil, Road test**

I. Introduction

Japan aims to achieve carbon neutrality by 2050, and electric vehicles (EVs) are being promoted as a means of achieving this goal. However, electric vehicles account for only a very small percentage of new car sales in Japan, and their use is not yet widespread. Factors preventing the spread of EVs include their short cruising range, charging time, and charging speed.

Wireless power transfer while driving is being considered as a solution to these problems. Wireless power transfer while driving is a technology that can reduce the cost and improve the cruising range of EVs by eliminating the need for recharging and the need to install large-capacity batteries and is being actively studied in many countries.

The transmission coil must be buried in the road as a method of wireless power transfer while driving, but it has been reported that burying the coil deteriorates the electrical characteristics of the coil [1]-[8].

In addition, for practical use, both mechanical characteristics, such as durability and coil protection equivalent to or better than normal road pavement as infrastructure, and electrical characteristics, such as deterioration of coil characteristics due to burial and maintenance of coil characteristics to reduce the number of maintenance cycles, are required.

In this paper, eight coils were installed in two locations, one between the wheels and the other under the wheel running position, using MMA (Methyl Methacrylate) resin mixture, at a pavement running test site where full-scale pavement and traffic loads can be evaluated, A comparison of electrical characteristics, efficiency, and power before and after the test was conducted.

II. Driving Tests at the Pavement Driving Test Track at the Public Works Research Institute

In this experiment, coil installation tests and driving load tests were conducted at the pavement driving test site in the Public Works Research Institute, where both electrical and mechanical characteristics can be evaluated simultaneously, to verify the durability of the pavement before and after driving and the electrical characteristics of the coil. Fig. 1 shows the pavement driving test site, and Fig. 2 and Table 1 show the specifications of the large vehicles. At the test site, four large vehicles run on a circular track that includes the coil burial area, running a total of 100,000 wheels (5t wheel load equivalent). The vehicle is controlled by an automated system that combines RTK-GPS and fiber-optic gyro to obtain an accurate location from GPS satellites and control the vehicle by determining its tilt and direction with the fiber-optic gyro, thereby enabling the vehicle to travel unmanned at a speed of 30 km/h and a running position of ±250 mm.

The location of the embedded coil and the traveling position of the heavy-duty vehicle are shown in Fig. 3. B.W.P (Between Wheel Path) indicates the position between the wheels of the vehicle, and I.W.P (Inner Wheel Path) indicates the inner wheel traveling position. The number of durable wheels on the pavement is 1 million wheels/decade for N5 traffic (planned pavement traffic between 250 and 1000 [vehicles/day・direction]) and 7 million wheels/decade for N6 traffic (planned pavement traffic between 1000 and 3000 [vehicles/day・direction]). Assuming a wheel passing probability of about 2.4% when coils are embedded in B.W.P, the number of wheels passing B.W.P is 24,000 wheels/decade for N5 traffic and about 168,000 wheels/decade for N6 traffic. In this verification, a traveling test equivalent to 100,000 wheels was conducted with a wheel load of 5t equivalent. Therefore, the durability evaluation period of coils embedded in I.W.P is estimated to be equivalent to about 42 years assuming that they are embedded in B.W.P on roads with N5 traffic, and about 6 years when they are embedded in B.W.P on roads with N6 traffic.

Fig. 1. Pavement driving test site.

Fig. 2. Load truck traveling at the coil embedment site.

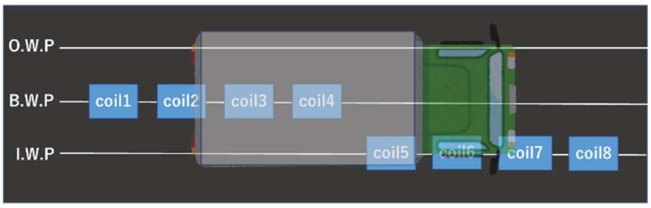


Fig. 3. Coil embedment point.

Table. 1. Loaded vehicle specifications.

Vehicle weight specifications	Numerical value
Vehicle weight	118.5 kN
Loading weight	206.0 kN
Gross vehicle weight	324.5 kN
Front wheel Fr	34.7 kN
Rear front wheel Fr1	63.8 kN
Rear wheel Fr2	63.8 kN

III. Embedment Coil

A total of eight transmission coils were embedded, four each in the B.W.P and I.W.P of the circular runway. The coils used for the embedment are shown in Fig. 4, the receiver coil in Fig. 5, and the dimensions of the coils are shown in Table 2. There are two types of power transmission coils: caseless coils and case coils, both with a coil size of 600 × 1700 mm, 6 turns, and a pitch of 12 mm. The case was made of polycarbonate resin. The conductors used to make the coils were FEP-coated litz wires with 10,000 strands, a strand diameter of 0.05 mm, and an allowable current of 96 A.

The original coil terminal was 3 m long, but was extended by 7 m using 4,000 strands of litz wire with a strand diameter of 0.05 mm for measurement while the coil was traveling, for a total terminal length of 10 m. The extension method is shown in Fig. 6. The electrical characteristics of the coil before embedment were measured before and after the terminal extension. Before the terminal extension, the internal resistance was 41.9 mΩ, inductance was 101.3 μH, and Q-factor was 1289, but after the terminal extension, the internal resistance changed to 116.6 mΩ, inductance was 116.1 μH, and Q-factor was 531.

Fig. 4. Embedment coil.

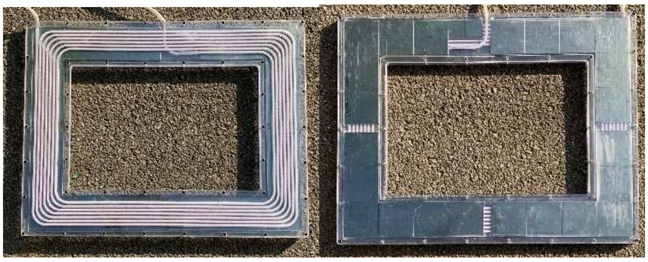


Fig. 5. Receiver coil

Table. 2. Coil parameters.

	Embedment coil	Receiver coil
Coil size [mm]	600×1700	600×800
Number of turns	6	15
Line pitch [mm]	12	11
Conductor diameter [mm]	7.85	7.85

Fig. 6. Terminal extension method.

IV. EMBEDMENT METHOD

Asphalt road has the following structure from the bottom: roadbed, binder layer, and surface layer. The coils were embedded in the binder layer and surface layer. The thicknesses of the binder and surface layers are 50 mm each. The method of embedment was the construction with MMA resin mixture proposed in a previous study [5]. Coils were embedded in four locations: in the binder and surface layers of B.W.P. and in the binder and surface layers of I.W.P. In all cases, one case coil and one caseless coil were embedded.

Fig. 7 shows the cross section of the asphalt road, Fig. 8 shows the construction method, and Figs. 9 and 10 show the construction procedure using MMA resin mixture. The areas where coils were to be installed in the binder and surface layers were cut and removed after paving, the MMA resin mixture was spread there, the coils were installed after the resin hardened, and then the resin mixture was spread over the coils for embedment. The case coil was pressurized so that no voids remained between the case and the resin mixture on the underside.

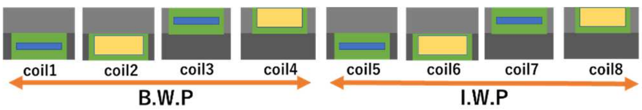
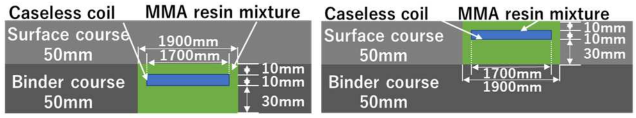
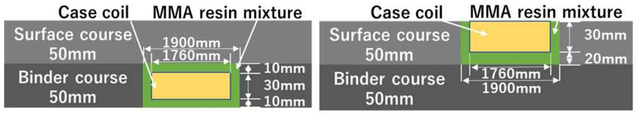


Fig. 8. Cross section of asphalt pavement.



(a)Binder course (coil1, coil5) (b)Surface course (coil3, coil7)

A) Caseless coil

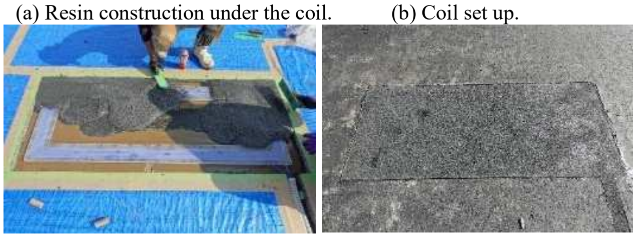


(a)Binder course (coil2, coil6) (b)Surface course (coil4, coil8)

B) Case coil

Fig. 7. Construction method by MMA resin mixture.

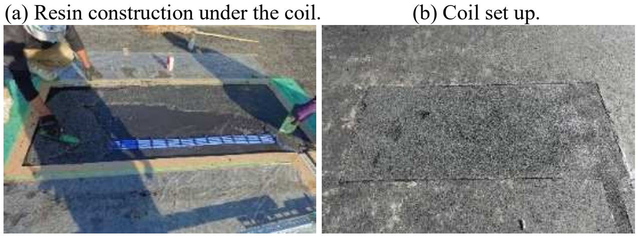
(a) Resin construction under the coil. (b) Coil set up.



(c) Resin construction on the coil. (d) After construction.

Fig. 9. Case coil construction procedure.

(a) Resin construction under the coil. (b) Coil set up.



(c) Resin construction on the coil. (d) After construction.

Fig. 10. Caseless coil construction procedure.

V. COMPARISON OF ELECTRICAL CHARACTERISTICS BEFORE AND AFTER TRAVELING TEST BY HEAVY-DUTY VEHICLE

Fig. 11 shows the road surface before and after the 100,000 wheels (5t wheel load equivalent) driving test by a heavy-duty vehicle; neither I.W.P nor B.W.P showed any damage to the pavement surface or the coil itself due to the driving of the heavy-duty vehicle, confirming that the MMA resin mixture can maintain sufficient strength in the construction.

Next, the electrical characteristics before and after the traveling test are described: the internal resistance R, inductance L, and Q-factor of the coil at 85 kHz were measured using an impedance analyzer (E4990A) from keysight. The transmission efficiency η and output power P between the transmitter and receiver coils were measured using a vector network analyzer (E5061B). All transmission distances were fixed at 200 mm, input voltage was measured at 600 V converted, and the load R_L was set to a value just barely not over 96A, the allowable current of the litz wire, and power and efficiency were measured. The magnetic field resonant coupling method is used in this paper, and the circuit topology is a series-series circuit with capacitors connected in series with the transmitter and receiver coils, respectively. The measurement scene is shown in Fig. 12.

Fig.13-15 show the measurement results of internal resistance R, inductance L, and Q-factor of the coils before and after the traveling test. The resistance of coil6 and coil7 increased by 1.22 and 1.39 times, respectively, before and after traveling. Fig. 14 shows that the inductance L decreased in all coils, but there was no significant change. Comparing the Q-factor from Fig. 15, the coil6 and coil7, where the increase in resistance was remarkable, decreased by about 30 % and 40 %, respectively, but there was no significant change in Q-factor for the other coils, it was confirmed that construction with MMA resin mixture can suppress the effect of running on the coils.

Fig. 16 and Fig. 17 show the measurement results of output power P and transmission efficiency η between the transmitter and receiver coils before and after the traveling test. In coil7, the output power and transmission efficiency decreased by 4.3 kW and 10.4 %, respectively, which is considered to be directly affected by the wheel load of large vehicles, since the caseless coils are embedded in the surface layer of the I.W.P. The output power and transmission efficiency of coil5, coil6, and coil8 embedded in other I.W.P. coils showed little change even after traveling. coil5 and coil6 are embedded in the binder layer, so the distance from the road surface is secured, and coil8 is in the surface layer but protected by a case and MMA resin mixture. The influence of the traveling of large vehicles was reduced by the protection by the case and MMA resin mixture in coil8, although it is a surface layer. In addition, it was found that the influence of the change in B.W.P over time could be suppressed by the construction using the MMA resin mixture because there was no significant change in both output power and transmission efficiency after 68 days had elapsed from the pre-travel to the post-travel measurements.

These results confirm that the MMA resin mixture is suitable and sufficient for coil embedment in terms of both mechanical strength and electrical properties. The output power and transmission efficiency were 46.4 kW and 81.2 %, respectively, for coil7, which is affected by running 100,000 wheels (5t wheel load equivalent), and for coils other than coil7, output power and transmission efficiency of 49 kW or higher and 88 % or higher were achieved. In particular, coil5 can achieve an output power of 51.2 kW and a transmission efficiency of 89.4% and is suitable for practical use because it does not use a case and is low cost.

(a) Pre-traveling (b) Post-traveling

Fig. 11. Road surface pre and post traveling.

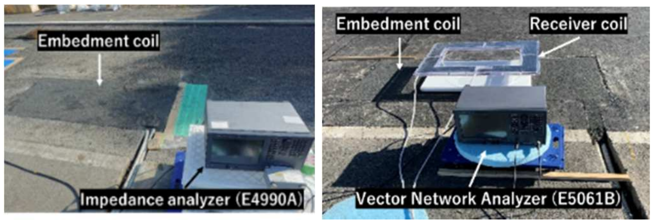


Fig. 12. Measuring Scenery.

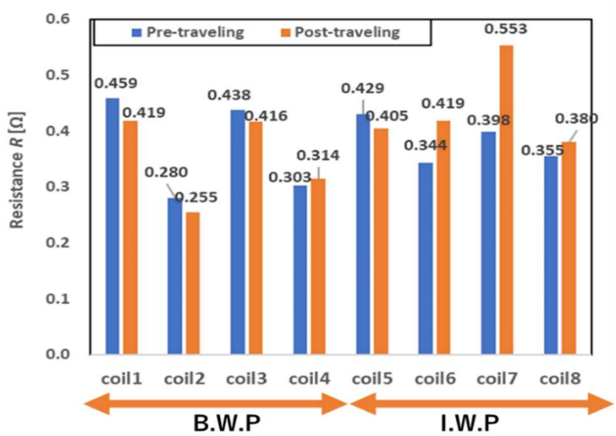


Fig. 13. Resistance R.

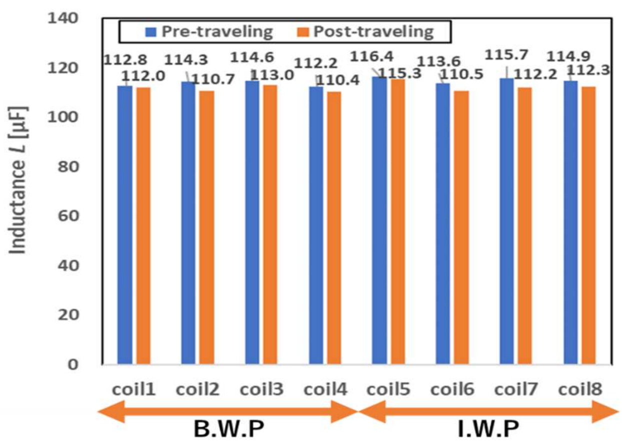


Fig. 14. Inductance L.

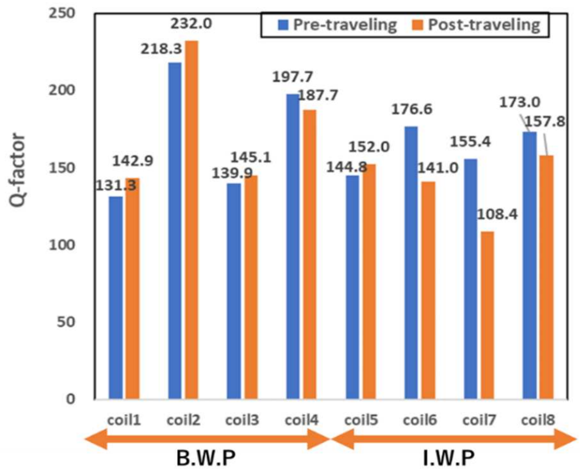


Fig. 15. *Q*-factor.

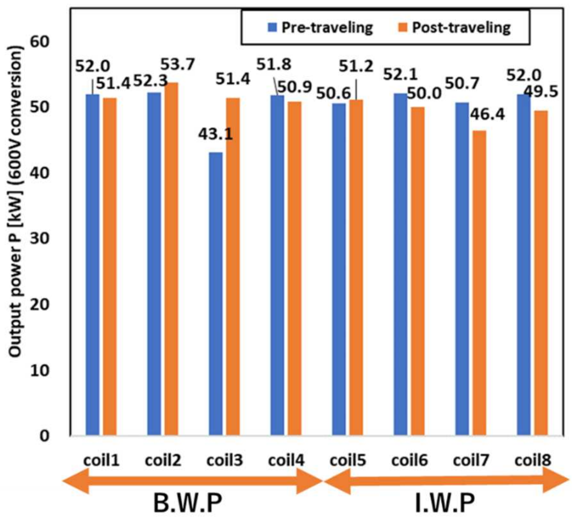


Fig. 16. Output power *P* (600V conversion).

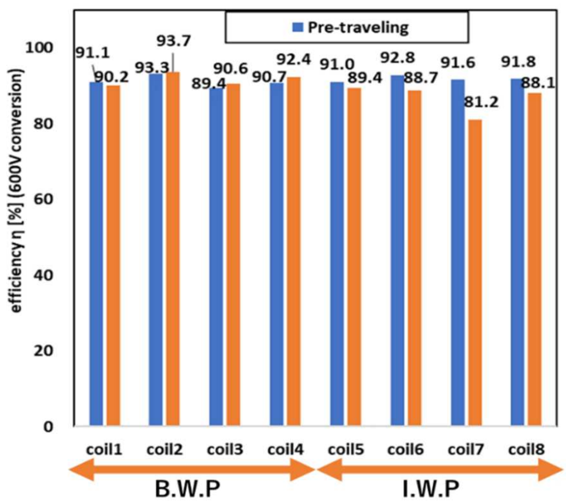


Fig. 17. efficiency η (600V conversion).

VI. Conclusion

In this paper, tests were conducted at the pavement driving test site in the Public Works Research Institute, where the mechanical strength and electrical characteristics of the coils can be evaluated simultaneously, to test the embedment of transmitter coils and the driving of a large vehicle with a design wheel load equivalent to 5t, which is approximately 100,000 wheels (5t wheel load equivalent). The coils were embedded at B.W.P. for operation on actual roads and at I.W.P. to simulate the traveling of large vehicles. At these two locations, a total of eight coils were embedded in the binder and surface layers in the asphalt pavement, using MMA resin mixture, and the road surface condition and electrical characteristics were compared before and after the large vehicle traveling test.

As a result, neither the road surface nor the coils themselves were damaged by the driving of heavy-duty vehicles at all of the embedded locations. As for electrical characteristics, the caseless coil embedded in the surface layer of the I.W.P. showed a decrease of 4.3 kW in output power and 10.4% in transmission efficiency, but the other seven coils showed no significant deterioration in characteristics, and it was confirmed that sufficient power could be supplied, with output power of 49 kW or more and transmission efficiency of 88 % or more after traveling. Especially, the caseless coil embedded in the binder course of I.W.P can achieve an output power of 51.2 kW and a transmission efficiency of 89.4% and is suitable for practical use because it does not use a case and is low cost.

The results indicate that the use of a coil case and MMA resin mixture to protect the surface layer of the coil can ensure durability, while the use of an MMA resin mixture for the binder layer of the coil, even for caseless coils, can suppress the effects of traveling load and aging.

Based on the above, we believe that the use of MMA resin mixture is a promising candidate for the construction method of coil embedment, both mechanically and electrically. In the future, we will further evaluate the mechanical and electrical properties of the coils when driven by large vehicles and investigate coils suitable for embedment in asphalt pavement.

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References

[1] R. Tavakoli and Z. Pantic, "Analysis Design and Demonstration of a 25-kW Dynamic Wireless Charging System for Roadway Electric Vehicles", IEEE Journal of Emerging and Selected Topics in Power Electronics, Sep 2018.

[2] R. Ahmad, V. Kumar, M. Bilal and S. Kumari, “Dynamic Wireless Power Transfer (DWPT) for Charging Application of Electric Vehicle,” 2022 1st International Conference on Sustainable

Technology for Power and Energy Systems (STPES), SRINAGAR, India, 2022.

[3] Cirimele, V.; Torchio, R.; Virgillito, A.; Freschi, F.; Alotto, P. Challenges in the Electromagnetic Modeling of Road Embedded Wireless Power Transfer. *Energies* 2019.

[4] V. Cirimele, M. Diana, F. Freschi and M. Mitolo, "Inductive Power Transfer for Automotive Applications: State-of-the-Art and Future Trends," in *IEEE Transactions on Industry Applications*, vol. 54, no. 5, pp. 4069-4079, Sept.-Oct. 2018.

[5] Koki Hanawa, Takehiro Imura, Yoichi Hori and Nagato Abe , "Proposal of Coil Embedment Method by Pouring Resin Materials for Dynamic Wireless Power Transfer", IEEE Wireless Power Week Conference (WPW 2022), Bordeaux, France, July 2022.

[6] Takehiro Imura, Koki Hanawa, Kanta Sasaki and Nagato Abe, "Coil Performance and Evaluation of Pavement Durability of Dynamic Wireless Power Transfer Systemusing Ferrite-less and Capacitor-less Coil for Road Construction Methods," 5th International Electric Vehicle Technology Conference (EVTeC2021), May. 2021

[7] Z. Feng, O. Shimizu, H. Sumiya, S. Nagai, H. Fujimoto and M. Sato, "Influence of Contamination Between Receiver Coil and Embedded Transmitter Coil for Dynamic Wireless Power Transfer System," 2021 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW), San Diego, CA, USA, 2021, pp. 1-6.

[8] F. Li, X. Sun, S. Zhou, Y. Chen, Z. Hao and Z. Yang, "Infrastructure Material Magnetization Impact Assessment of Wireless Power Transfer Pavement Based on Resonant Inductive Coupling," in IEEE Transactions on Intelligent Transportation Systems, vol. 23, no. 11, pp. 22400-22408, Nov. 2022.

[9] H. Wang, U. Pratik, A. Jovicic, N. Hasan and Z. Pantic, "Dynamic Wireless Charging of Medium Power and Speed Electric Vehicles," in *IEEE Transactions on Vehicular Technology*, vol. 70, no. 12, pp. 12552-12566, Dec. 2021.

[10] T. Goetz, A. Baehr and N. Parspour, "Contribution to the Coupling Behavior Analysis of WPT Systems for Electric Vehicles with Flush Ground and Buried Primary Side Mounting," *2022 IEEE 7th Southern Power Electronics Conference (SPEC)*, Nadi, Fiji, 2022.

[11] S. Inoue, C. R. Teeneti, D. Goodrich, J. Larsen, A. Kamineni and R. Zane, "High-Power Field-Focusing Circuit for Dynamic Wireless Power Transfer Systems," *2022 Wireless Power Week (WPW)*, Bordeaux, France, 2022.

[12] Yuto Yamada Takehiro Imura, "An Efficiency Optimization Method of Static Wireless Power Transfer Coreless Coils for Electric Vehicles in the 85 kHz Band Using Numerical Analysis", *IEEJ Transactions on Electrical and Electronic Engineering IEEJ Trans 2022*, vol.17, Issue 10, pp. 1506-1516, October. 2022.

[13] S. Kim *et al*., "Thermal Evaluation of an Inductive Power Transfer Pad for Charging Electric Vehicles," in *IEEE Transactions on Industrial Electronics*, vol. 69, no. 1, pp. 314-322, Jan. 2022.

[14] R. M. Nimri, A. Kamineni and R. Zane, "A Modular Pad Design compatible with SAE J2954 for Dynamic Inductive Power Transfer," *2020 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*, Seoul, Korea (South), 2020.

[15] Y. Yamada, T. Imura and Y. Hori, "Theorizing a Simple Ferrite Cored Coil Using Image Coils in Wireless Power Transfer," in IEEE Access, vol. 11, pp. 8065-8072, 2023.

[16] K. Hanawa, T. Imura, Y. Hori and N. Abe, "Comparison of Circular Coil, Double-D Coil, and 85 kHz Self-Resonant Coil in Road Embedment for Dynamic Wireless Power Transfer," *IECON 2022 – 48th Annual Conference of the IEEE Industrial Electronics Society*, Brussels, Belgium, 2022.