Report on the 4-Year Burial of 41 Coils for Dynamic Wireless Power Transfer in Asphalt Roads

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ABSTRACT: For dynamic wireless power transfer, the development of technology for embedding the coils in the road is important. In order to embed coils in the road, both electrical and mechanical properties are required. This study spans four years of embedding coils in asphalt roads on the Tokyo University of Science campus to evaluate their electrical and mechanical characteristics. A total of 41 coils were installed over a total length of 99.9 m. Adjustments to the design and installation methods were made to test performance. As a result, 20 of the coils installed in 2022 and 2023 met the required standards, including mechanical characteristics. An efficiency of 94% and an output equivalent to 50kW (calculated at an input voltage of 600V) were achieved, demonstrating successful development of a coil design and installation technique suitable for practical use.

KEY WORDS: Dynamic wireless power transfer, road paving, asphalt roads, electric vehicles

1. Introduction

Global warming is an unavoidable issue, and the transport sector is no exception. Dynamic Wireless Power Transfer (DWPT) is being explored as a sustainable solution to reduce CO_2 emissions in this sector. Research on DWPT for powering vehicles in motion is being conducted worldwide[(1),(2)]. This technology is based on the premise of embedding coils, but there are few reports of embedded coils[(3)-(7)]. Furthermore, there are very few studies that aim to combine electrical and mechanical properties, although a predecessor report to this project has been published[(8)-(15)].

In this paper, four years of research on embedding coils in asphalt roads on the Tokyo University of Science campus is outlined. A total of 41 coils were embedded in the road over a total length of 99.9 m. Variations in the coil design and installation methods were applied to evaluate their electrical and mechanical characteristics.

2. An overview of the coil burial project from fiscal years 2020 to 2023

The research and development of coil burial technology for DWPTs in this paper is part of the MLIT "Research and Development of Technology to Improve the Quality of Road Policy" project. The project aims to bury coils in asphalt roads and establish coils and construction methods that can be used on public roads with both electrical and mechanical properties. In FY2020, a feasibility study (FS) will be conducted for one year, after which the project will transition to a three-year full-scale study.

2.1. DWPT Roads and Coils Location

The experiment is conducted on a 110 m DWPT road in the Noda campus of Tokyo University of Science. Each year, an experimental coil burial section of approximately 22–26 m was used. Over multiple years, this resulted in a total length of 99.9 m (Fig.1, Fig.2).

Fig.1 Photo after completion of coil burial work

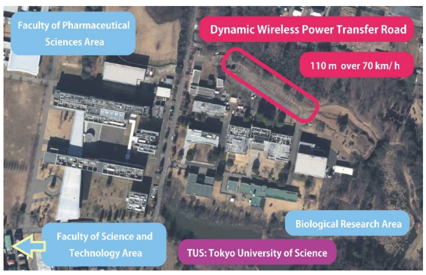
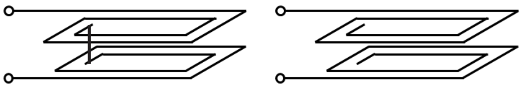


Fig.2 Aerial view of the DWPT section. Prepared by processing an aerial photograph taken by the GSI (2013).

2.2. Electrical characteristics of coils

There are two types of coils. One is an open-type coil, which is also called a ferrite-less and capacitor-less coil. The open-type and short-type coils are shown in Fig.3. The open-type coil utilizes self-resonance due to stray capacitance and therefore does not require an external resonant capacitor. Moreover, it does not require ferrite because it is sufficiently efficient. As a result, only a Litz wire is needed to form the coil, enabling cost reduction compared to conventional short-type coils. However, achieving resonance at 85 kHz and high power is challenging due to its high impedance compared to the short-type coil.



(a) Short type (b) Open-type

Fig.3 Schematic of open and short coils

2.3. FWD test and road durability

The FWD test is a test using a device that simultaneously measures the amount of deflection that occurs on the pavement surface when a weight is dropped on the road surface at multiple points. Based on the measured deflection, it is possible to calculate the usable life of the road. FWD test is shown in Fig.4.

Fig.4 The FWD test scene

3. Implementation details of the coil burial project from fiscal years 2020 to 2023

The power was calculated based on the electrical characteristics at low power and converted accordingly, with an input voltage of 600 V, consistently throughout this paper. In the experimental measurements, an impedance analyzer (E4990A) was used for coil parameter measurements, and a vector network analyzer (VNA) (E5061B) was used for efficiency measurements. To examine the impact of embedding, this paper standardizes the power transmission distance to 200 mm between coils. Therefore, this distance does not refer to the distance from the ground to the receiving coil.

3.1. Implementation details for fiscal year 2020[8]

In fiscal year 2020, 7 coils were embedded over a section of 22.7 m. These consisted of 6 capacitor-less types and 1 standard coil that required a resonant capacitor (Fig.5). All coils were installed at base course (Fig.6). In this year, the road is aimed at designing a road design that can withstand N5 traffic volume equivalent. Q is from 26 to 191 (Fig.7). The best-performing coil achieved an efficiency of 97% and an output of 3.4kW. A Litz wire with a strand diameter of 0.1 mm and 460 strands was used, and the load was set to the optimal value for maximum efficiency. Mechanical road durability was estimated to range from 1.4 to 6.8 years, with a 2.4% probability of being directly run over by vehicle tires. Overall, none of the coils succeeded in achieving a balance between electrical and mechanical characteristics in this fiscal year.

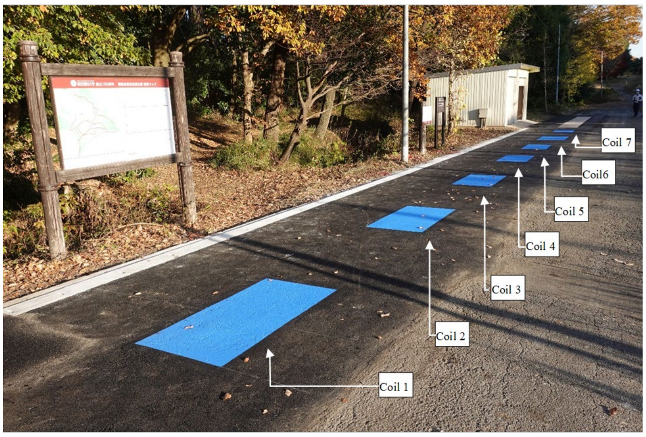


Fig.5 Embedded 7 coils in 2020

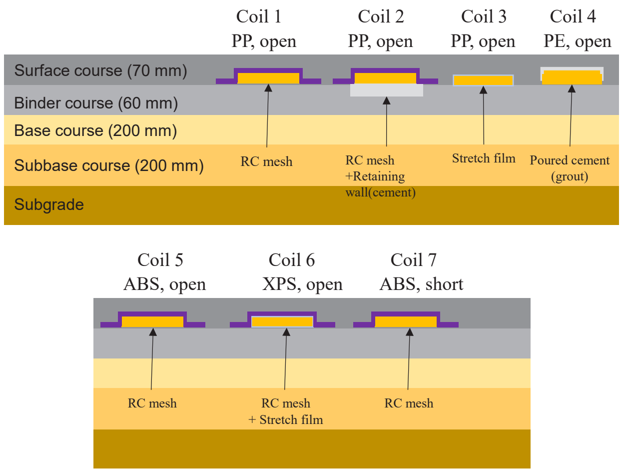


Fig.6 Cross-sectional view of the location and depth of the buried coil and the burial method in 2020

Table 1 Characteristics of buried coil, No. is the coil number, O is open type, S is short type **in 2020**

No.		Feature (Common to all: Coil dimensions 1300 mm × 600 mm)
1	O	PP, RC mesh
2	O	PP, RC mesh, retaining wall (cement)
3	O	PP, stretch film
4	O	PE, poured cement (grout)
5	O	ABS, RC mesh
6	O	XPS, stretch film, RC mesh
7	S	Acrylic + PC + ABS, RC mesh, ferrite

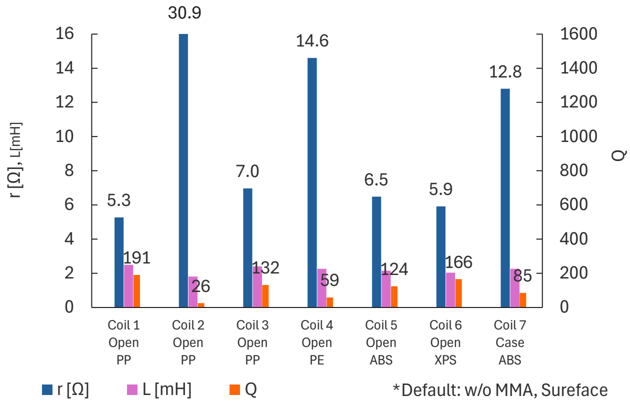


Fig.7 Coils parameters (r, L, Q) in FY2020

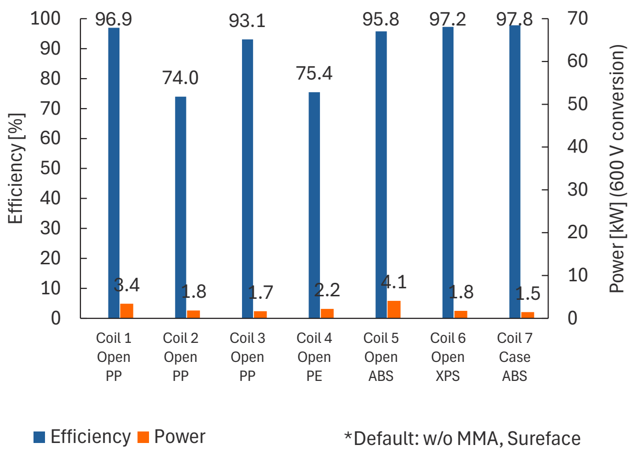


Fig.8 Efficiency and output power in FY2020 (Optimal load)

3.2. Implementation details for fiscal year 2021[(12)]

In fiscal year 2021, 11 coils were embedded over a section of 25.7 m. These included 4 capacitor-less types and 7 standard coils (Fig.9). Installation depths varied, with two coils in the surface course, eight in the binder course, and one in the base course (Fig.10). From this year, the road is aimed at designing a road design that can withstand N6 traffic volume equivalent. Resin was also poured around the coils as an improvement, and a comparison between Coil 5 and Coil 7, as well as between Coil 9 and Coil 10, confirmed an increase in the Q-value. Q is from 74 to over 1000 (Fig.11). To achieve high-power operation, the load was set to allow current up to the permissible level of the transmission-side Litz wire. From this year, the maximum current load condition was established as the standard load condition. A Litz wire with a strand diameter of 0.05 mm and 4,000 strands, capable of carrying up to 38 A, was used, and the load value was adjusted to ensure a maximum current of 38 A. The best-performing coil achieved an efficiency of 95.6% and an output of 21.5kW (Fig.12). Mechanical durability ranged from 2 to 22 years for open-type coils and 4 to 17 years for short-type coils; as the road design lifespan was set at 10 years, values exceeding this are reference estimates. From this year onward, a 100% probability of direct load impact was assumed. Overall, three coils achieved 90% efficiency and 20 kW output, confirming a balance between electrical and mechanical characteristics (Table 3).

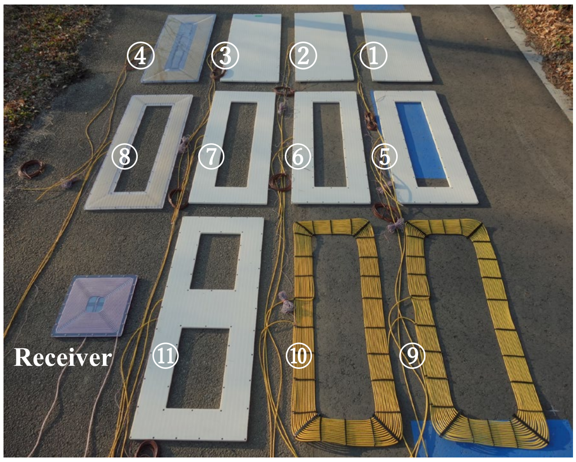


Fig.9 Picture of 11 types of transmission coils and 1 receiving coil in FY 2021

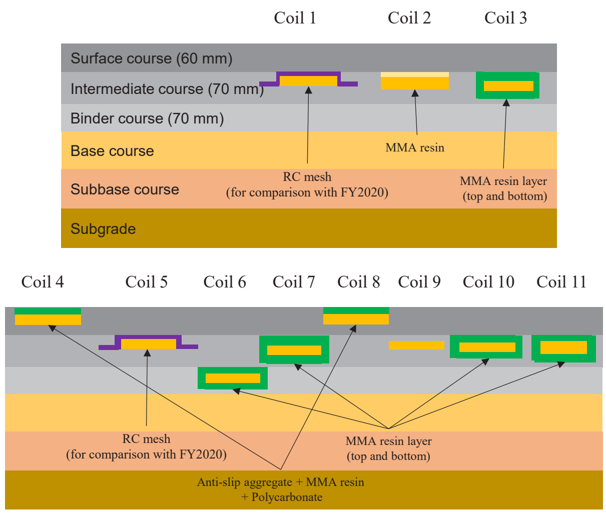


Fig.10 Cross-sectional view of the location and depth of the buried coil and the burial method in 2021

Table 2 Characteristics of buried coil, No. is the coil number, O is open type, S is short type **in 2021**

No.		Feature (Common to all: Coil dimensions 1600 mm × 600 mm)
1	O	Reference coil, for comparison with last year, RC mesh, no adhesive with pavement
2	O	Adhesive only, MMA resin and silica sand (3mm) on top, adhesive below
3	O	Resin isolation, top and bottom MMA resin poured (20 mm)
4	O	Surface setting, adhesives only, MMA resin and silica sand (3mm) on top, adhesive below
5	S	Reference coil, for comparison with last year, RC mesh, no adhesive with pavement
6	S	Base course installation, resin isolation, top and bottom MMA resin poured (20 mm)
7	S	Resin isolation, top and bottom MMA resin poured (20 mm)
8	S	Surface setting, adhesives only, MMA resin and silica sand (3mm) on top, adhesive below
9	S	Caseless, direct burial (no adhesive)
10	S	Caseless, resin isolation, top and bottom MMA resin poured (20 mm)
11	S	DD coil, resin isolation, top and bottom MMA resin poured (20 mm)

Table 3 Overall evaluation in 2021

	Coil 1	Coil 2	Coil 3	Coil 4
Q	155	73.6	174	128
Efficiency [%]	90	89.2	90.0	90.1
Power [kW]	5.69	1.93	6.45	4.18
Allowable year of load wheels [years] (N6)	2.0	10.8	3.8	22.3
	Coil 5	**Coil 6**	**Coil 7**	**Coil 8**
Q	268	464	471	275
Efficiency [%]	92.6	94.1	93.5	93.4
Power [kW]	20.4	20.6	21.2	21.2
Allowable year of load wheels [years] (N6)	4.1	14.0	4.7	14.8
	Coil 9	**Coil 10**	**Coil 11**	
Q	264	371	1053	
Efficiency [%]	90.2	94.2	95.6	
Power [kW]	12.3	21.2	21.5	
Allowable year of load wheels [years] (N6)	16.7	10.9	5.8	

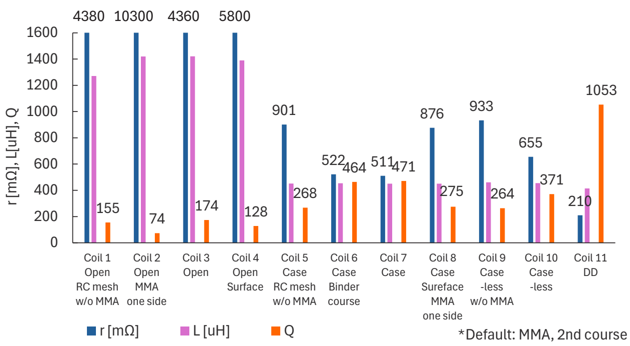


Fig.11 Coils parameters (r, L, Q) in FY2021

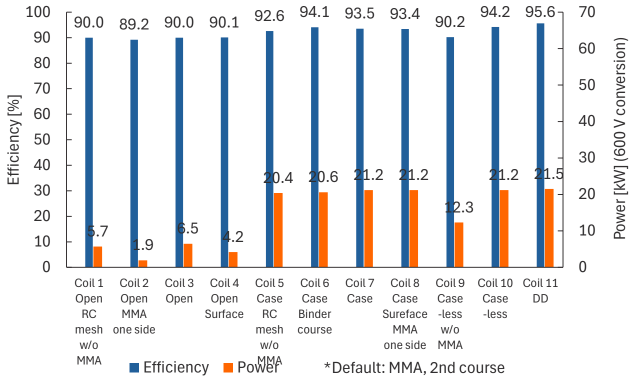


Fig.12 Efficiency and output power in FY2021 (Max current load)

3.3. Implementation details for fiscal year 2022[13]

In fiscal year 2022, 10 coils were embedded over a section of 25.7 m. These included 1 capacitor-less type and 9 standard coils (Fig.13). The installation depths included 7 coils in the surface course and 3 in the binder course (Fig.14). From fiscal year 2022 onward, a Litz wire with a strand diameter of 0.05 mm and 10,000 strands, capable of carrying up to 96 A, was used. The load value was adjusted to ensure a maximum current of 95 A (Fig.13). Q is from 230 to 830 (Fig.15). The best-performing coil achieved an efficiency of 96.8% and an output of 55.6kW (Fig.16). All coils demonstrated mechanical durability exceeding 20 years. Overall, all 9 short-type coils achieved 94% efficiency and 50 kW output, demonstrating a balance between electrical and mechanical characteristics.

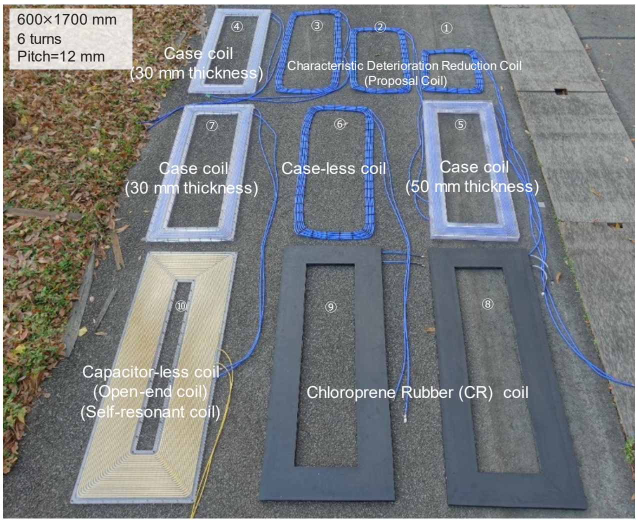


Fig.13 Picture of 10 transmitting coils in FY 2022

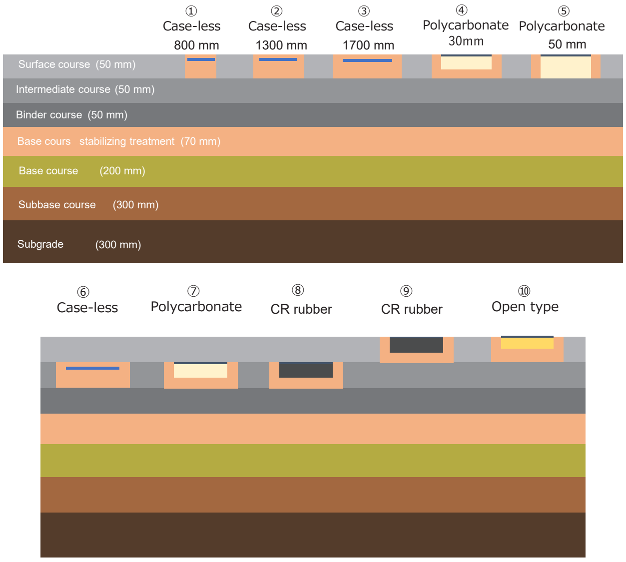


Fig.14 Cross-sectional view of the location and depth of the buried coil and the burial method in FY2022

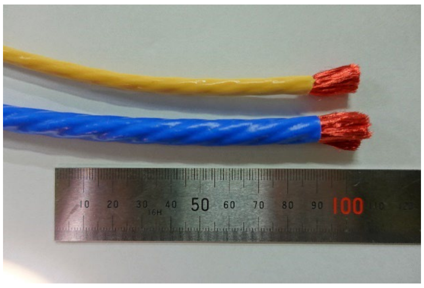


Fig.15 Comparison of Litz wires with 4,000 strands (yellow) and 10,000 strands (blue).

Table 4 Characteristics of buried coil, No. is the coil number, O is open type, S is short type **in 2022**

No.	Feature (Normal coil dimensions 1700 mm × 600 mm, Common to all: MMA)	
1	S	Case-less, length: 800mm, surface course
2	S	Case-less, length: 1300mm, surface course
3	S	Case-less, length: 1700mm (normal), surface course
4	S	Case, thickness: 30mm, surface course
5	S	Case, thickness: 50mm, surface course
6	S	Case-less, intermediate course
7	S	Case, intermediate course
8	S	CR rubber case, intermediate course
9	S	CR rubber case, surface course
10	O	Surface course

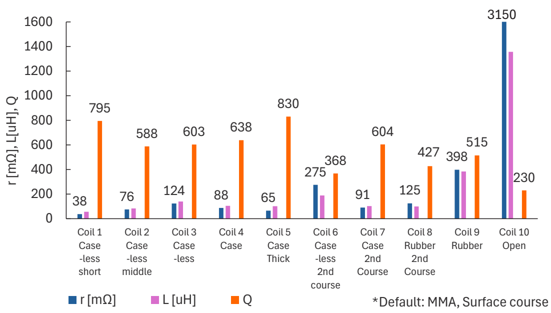


Fig.16 Coils parameters (r, L, Q) in FY2022

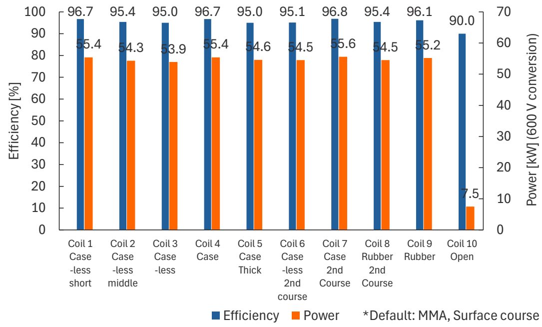


Fig.17 Efficiency and output power in FY2022 (Max current load)

3.4. Implementation details for fiscal year 2023

In fiscal year 2023, 13 coils were embedded over a section of 25.8 m. These included 1 capacitor-less type and 12 short type coils, all installed in the surface course. (Fig.17, Fig.18, Fig.19). Coil 4 is embedded at a depth of 0 mm, while all other coils are embedded at a depth of 10 mm. Embedding the coil in the surface layer has the advantage of making the coil-to-coil distance almost identical to the ground-to-receiving coil distance.

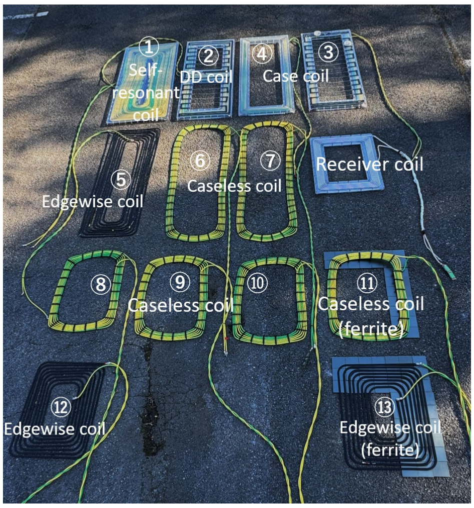


Fig.18 Coils in FY 2023 (Note: Ferrite is fully applied to the bottom of coil No.13)

Especially, the edgewise coil is fabricated using a flat copper plate, making it highly cost-effective. Q is from 230 to over 1000.The best-performing coil achieved an efficiency of 97.6 % and an output of 55.8 kW (Fig.20, Fig.21). Mechanical durability exceeded 20 years for all except the open-type coils. Overall, eleven short-type coils achieved 94% efficiency and 50 kW output at max current load, demonstrating a balance between electrical and mechanical characteristics. Stable characteristics can be achieved even when embedded in the surface layer, as similar data were obtained from multiple coils. In particular, it was demonstrated that this can be achieved using edgewise coils, which are significantly more cost-effective than Litz wires.

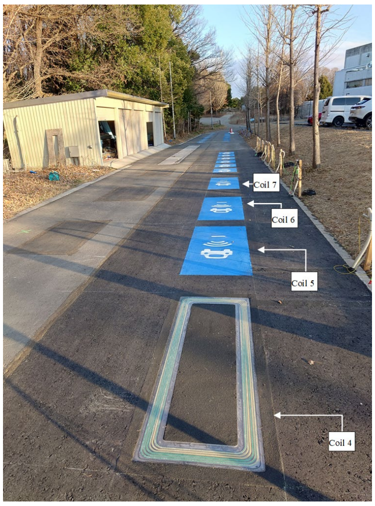


Fig.19 Embedded 13 coils in 2023 (Note: Coil4 to 13 is shown)

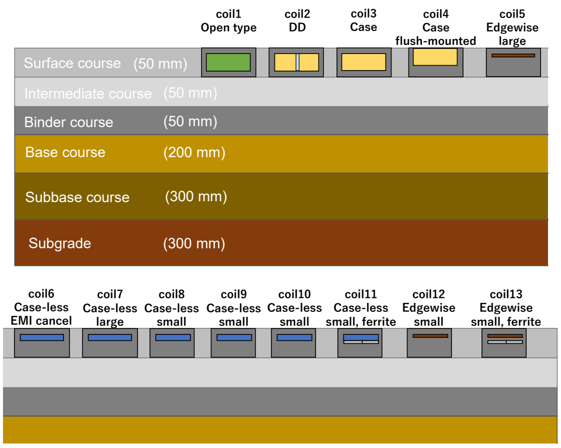


Fig.20 Cross-sectional view of the location and depth of the buried coil and the burial method in FY2023

Table 5 Characteristics of buried coil, No. is the coil number, O is open type, S is short type **in 2023**

No.		Feature (Normal coil dimensions 1700 mm × 600 mm, Common to all: MMA, surface course)
1	O	Open
2	S	DD
3	S	Case
4	S	Case, flush-mounted
5	S	Edgewise
6	S	Case-less
7	S	Case-less
8	S	Case-less, length: 800 mm (short)
9	S	Case-less, length: 800 mm (short)
10	S	Case-less, length: 800 mm (short)
11	S	Case-less, length: 800 mm (short), ferrite
12	S	Edgewise, length: 800 mm (short)
13	S	Edgewise, length: 800 mm (short), ferrite

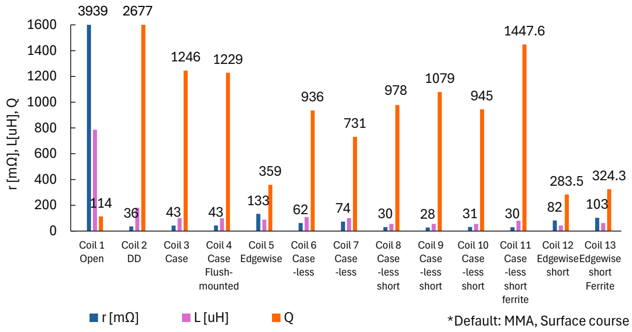


Fig.21 Coils parameters (r, L, Q) in FY2023

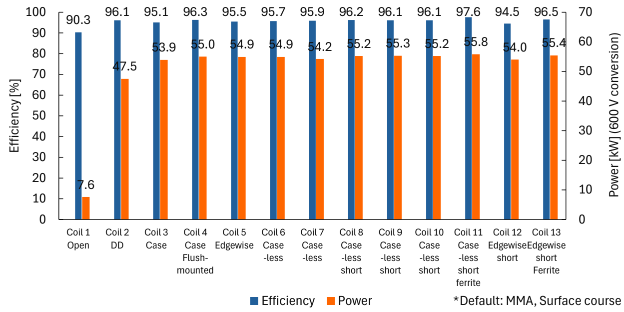


Fig.22 Efficiency and output power in FY2023 (Max current load)

Measurements were also conducted using the optimal load that achieves maximum efficiency(Fig.23). Under optimal load conditions, efficiency improves compared to the maximum current load condition; however, for 12 short-type coils (excluding the open-type), the increase is generally less than one percentage point. On the other hand, the power decrease is significant, reaching up to 26.1 kW (Coil 11). This indicates that designing for high power rather than strictly adhering to the maximum efficiency condition is preferable.

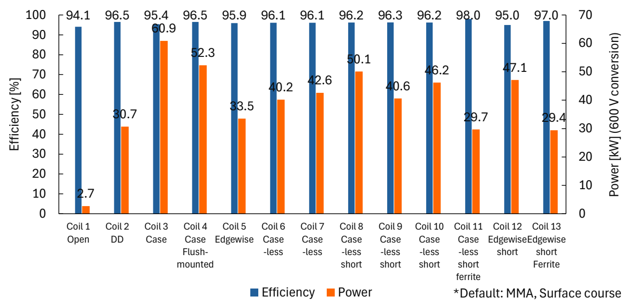


Fig.23 Efficiency and output power in FY2023 (Optimal load)

3.5. Summary of projects from fiscal years 2020 to 2023

Since standard coils (ferrite-free coils) have exceeded benchmark values since 2022, an upgraded version was introduced in 2023 with cost reduction in mind. This improved design and installation method achieved stable performance with 94%

efficiency and 50kW output (calculated at an input voltage of 600V), while also maintaining the mechanical strength needed for a 10-year road lifespan. In fiscal year 2023, edgewise coils were successfully introduced into the surface layer of asphalt roads for the first time.

4. Conclusion

Over the four-year period of this study, coil embedding technology for Dynamic Wireless Power Transfer (DWPT) was successfully tested and refined through extensive trials on asphalt roads at the Tokyo University of Science. A total of 41 coils were embedded with varying designs and depths to evaluate both electrical and mechanical performance. Through gradual improvements in coil design and installation methods, the study demonstrated that a balance of high electrical efficiency and durability can be achieved, with the final coil designs from fiscal years 2022 and 2023 meeting or exceeding required standards. These later iterations reached a stable efficiency of 94% and power outputs equivalent to 50kW, with mechanical durability ratings that support a 10-year road lifespan. Especially, in fiscal year 2023, edgewise coils were successfully introduced into the surface layer of asphalt roads for the first time.

Additionally, regarding load settings, switching to the optimal load condition that achieves maximum efficiency results in a slight efficiency increase compared to the maximum current load condition, generally less than one percentage point. However, the decrease in power is significant, reaching up to 26.1 kW (Coil 11). This suggests that prioritizing high-power design rather than strictly adhering to the maximum efficiency condition is preferable.

The findings underscore the feasibility of embedding DWPT coils in road infrastructure, providing a promising pathway for sustainable and continuous power delivery to electric vehicles. Notably, as technology advanced, installation methods were refined to meet both cost-effectiveness and performance benchmarks. This study has thus contributed valuable insights and practical benchmarks for DWPT implementation on public roads, paving the way for future research and broader adoption of wireless power transfer systems in the transportation sector.

Acknowledgement

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