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Feasibility Analysis of Dynamic Wireless Charging Highway

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Abstract:
Nowadays, electric vehicles are gradually replacing fuel vehicles. However, electric vehicles are restricted by battery and charging technology, and they still have significant shortcomings in terms of endurance and charging compared to fuel vehicles, which greatly restricts the application of electric vehicles. The most obvious example is that the application of electric vehicles is usually concentrated in urban areas, and few users will choose electric vehicles for long-distance travel. Dynamic wireless charging roads provide an almost permanent solution to this shortcoming, which enables electric vehicles to have nearly unlimited endurance. However, due to cost reasons, wireless charging roads are still a long way from large-scale commercialization. This article analyzes the technical principles of dynamic wireless charging roads and the experimental projects of dynamic wireless charging roads that have been carried out, and compares the charging technology of dynamic wireless charging roads with mainstream electric vehicle charging technologies in many aspects, and concludes and summarizes the significant advantages and future development direction of dynamic wireless charging road technology. And make predictions on the areas where dynamic wireless charging roads are most likely to be commercialized.

Keywords: Dynamic wireless charging highway, cost control, electric vehicle charging technology.

1. Introduction

With significant advantages such as cleanliness, environmental protection and low operating costs, electric vehicles (EV) have seen their penetration rate in the global transportation sector continue to rise, and they have gradually become a powerful alternative to traditional fuel vehicles. However, the current development of battery technology and charging infrastructure is lagging behind, resulting in issues of driving range and charging efficiency becoming the core bottlenecks restricting the further development of the electric vehicle industry. Taking a typical 300-kilometer range model as an example, a traditional fuel vehicle only takes 3-5 minutes to refuel, achieving a rapid replenishment of driving range; while for elec-

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tric vehicles with the same driving range, a single DC fast charge usually takes 1-2 hours, and if AC slow charging is used, the required time may even be as long as 6-8 hours [1]. This significant gap is particularly prominent in long-distance travel scenarios, greatly limiting the scope of application of electric vehicles, making them mainly concentrated in urban commuting and short-distance travel.

Dynamic Wireless Power Transfer (DWPT) is an innovative solution to the above problems. By integrating wireless energy transmission devices into road infrastructure, it can realize real-time charging of electric vehicles while driving. In theory, it can break through the limitations of traditional driving range and open up a new path for the development of electric vehicles. Research on wireless charging road technology can be traced back to the 1970s. As a pioneering exploration in this field, the US PATH project verified the feasibility of dynamic wireless charging technology for the first time. However, due to the limitations of the technology at the time, the project had problems such as low energy transmission efficiency (about 60%) and high construction cost (about US$1 million/km) [2]. In recent years, with the rapid development of power electronics technology, electromagnetic coupling technology and intelligent control technology, research and demonstration projects on wireless charging roads around the world have entered a rapid development stage.

However, due to the current technical level and construction costs, the commercialization of this technology still faces many challenges. At present, the unit construction cost of wireless charging roads is as high as millions of US dollars, which is difficult to meet the economic feasibility requirements of large-scale industrial applications [3]. The current research focus is gradually shifting to using wireless charging roads as a supplement to existing charging infrastructure, and improving the overall efficiency and economic benefits of the system through coordinated integration with traditional charging facilities such as charging piles and battery swap stations, or opening up dedicated charging lanes on highways [4]. Based on the existing research results, this paper will deeply explore the development trend of wireless charging road technology, key technical bottlenecks and its commercial application prospects.

2. The Technical Core of Dynamic Wireless Charging Highway

The technical core of the dynamic wireless charging highway is the Wireless Power Transfer System (WPTS), which can be divided into two core components. Its detailed structure is shown in Fig. 1. The power transmission subsystem buried in the road structure layer mainly includes key equipment such as the pavement structure layer, the supporting structure and the transmitting coil. The pavement structure layer and the supporting layer will determine the overall durability and service life of the highway, while the transmitting coil determines the charging efficiency; and the power receiving system for electric vehicles, including receiving coils, filters, AC-DC converters, etc. The receiving coil is responsible for realizing the energy reception of the pavement coil, while the converter is responsible for power conversion and power supply functions.

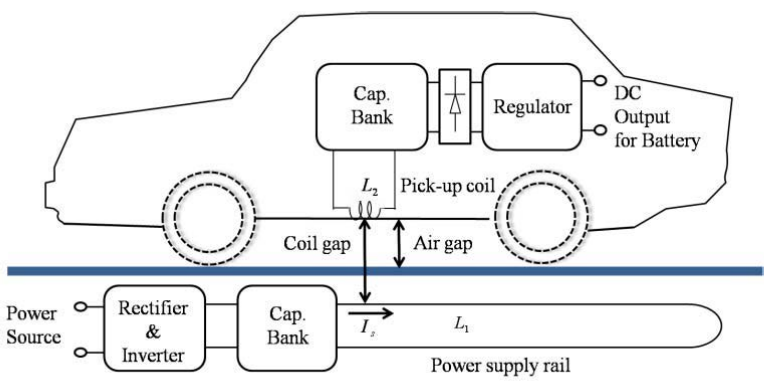

Fig. 1 Schematic diagram of road-powered electric vehicles using wireless charging technology [5]

2.1 Highway Infrastructure System

The pavement structure system of wireless charging roads can be divided into two functional modules: the inductive charging equipment module, which is located below the pavement structure layer and consists of a transmitting coil device and a magnetic core. Current technical research focuses on improving energy transmission efficiency and reducing energy loss. At the same time, it integrates an intelligent recognition system to dynamically control the opening and closing of equipment by real-time monitoring of the driving status of vehicles on the road, thereby achieving energy consumption optimization and efficiency improvement. And the pavement structure module. Studies have shown that the thickness of the pavement is negatively correlated with the wireless charging efficiency. A 110mm thick concrete slab will cause a power loss of 3.93W to the wireless charging system [6]. The performance of the pavement material directly affects the service life of the wireless charging road. Therefore, the pavement layer must meet the engineering performance requirements such as high temperature resistance, mechanical impact resistance, waterproof and corrosion resistance, and minimize the shielding effect on electromagnetic energy transmission while ensuring the road's use function.

2.2 Vehicle-Mounted Receiving Equipment System

on the vehicle side includes a receiving coil and a rectifier, which is responsible for converting the induced AC voltage into DC power for use by the vehicle drive system. Given that the current ground clearance of electric vehicle chassis has interval characteristics and the projection area of the chassis of a single model is relatively fixed, the key to this technology is to study the optimization of mutual inductance under fixed air gap conditions. Under the condition of constant ground clearance of the receiving coil, the mutual inductance coefficient of the vehicle-road coil is improved by designing different magnetic core, thereby improving energy transmission efficiency and reducing losses. The balanced design between transmission distance and durability, although shortening the coil spacing can significantly improve transmission efficiency, will lead to a decrease in vehicle road adaptability and an increase in the risk of equipment damage. Therefore, how to establish an optimal balance between energy transmission efficiency and system durability has become an important research topic in this technical field.

3. Economic Benefit Analysis of Wireless Charging Highway and Comparison with Existing Charging Technologies

3.1 Cost of Wireless Charging Highway

The cost of dynamic wireless charging roads can be basically divided into three parts: construction cost, long-term maintenance and operation cost of roads and equipment, and the cost of installing wireless charging road receiving systems on vehicles. Among them, the construction cost is the main body of the project, and its cost is much higher than the sum of the latter two. This is also the main dilemma facing wireless charging roads now - wireless charging roads are high-risk investments with high investment costs and low marginal costs. The balance between the investment cost recovery rate of infrastructure and public acceptance is one of the difficulties in realizing its industrialization. Without government support, the project is basically difficult to carry out. The project costs of various countries are shown in Table 1.

Table 1. Summary of wireless charging highway field test projects in various countries [7]

Countries and organizations	Project Name	Charging efficiency /%	Economic costs Per km	Structural details	Project Status
Korean Science Institute of Technology	OLEV (4th generation)	80	$ 850,000	Rail Road length 24 m; Receiving coil: 80× 100× 8 cm	Several city buses in Gumi City are being operated Wireless charging
EU FABRIC	Victoria	83	N/A	Track length 100 m; Transmitting coil 8, spacing 12.5 m, each 60× 80 cm ; receiving coil 60× 250 cm	In Turin, Italy, France's Sarto built a test track road, For trucks OK feel answer charge Electrical testing
Bombardier company	PRIMOVE	90	3.25 million ~6.15 million euros	Track length 800 m; Receiving coil 200× 100 cm; None Wire Charge part 4pcs , spacing 20 m	The road has integrated transmission components, but some Components not yet fully integrated into the vehicle

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Oak Ridge National Laboratory	WPT	95	1.32 million euros	Track length 3. 16 m; shoot Coil 70. 2× 70. 2 cm	Several Toyota models were used to test the wireless charging effect. High charging efficiency.

3.1.1 Highway Construction

At present, the focus of capital investment in wireless charging highway projects is concentrated on the highway construction stage. Taking the Korean OLEV project as an example, the cost of road section construction accounts for more than 80%. Based on the differences in construction technology, the construction methods of wireless charging highways can be divided into the following four categories: trough construction; micro-trough construction; cast-in-place full-paving construction; prefabricated full-paving construction. Detailed descriptions can be found in Table 2. The first two construction schemes are suitable for upgrading and renovating traditional pavements and have the advantage of low initial investment costs; while the latter two schemes are more suitable for new road projects, but there is a problem of long construction period [7]. Compared with traditional road construction, the incremental cost of wireless charging highways mainly comes from the electronic components such as transmitting coils and magnetic cores laid inside the road, as well as special treatment processes such as waterproofing and high temperature resistance implemented for these components. Limited by the level of technological development and material costs, it is difficult to achieve a significant reduction in these costs in the short term.

Table 2. Comparative analysis of wireless charging highway construction methods [7]

Construction method	Width/mm	Buried depth/mm	Significant advantages	Significant Disadvantages
trough construction	350~2 200	60~100	Shorter construction time; Lowest initial construction cost; Only 1 lane closure required; Less excavation waste	The life cycle cost may be higher (more repairs); Longitudinal and transverse power supply connections are introduced in the center of the lane
micro-trough construction	20~30	120~300	Short construction time; less excavation waste; guaranteed road surface structure Integrity; the use of special filling materials can make the cable load Less impact on load; good waterproof; easy maintenance/ replacement	The life cycle costs may be higher (more repairs); Two longitudinal and 1 horizontal Power connector
cast-in-place full-paving construction	Full lane width	60~100	Only a single longitudinal joint is required; potentially longer life than trough-type construction Lower life cycle costs	Long construction time; two-lane traffic control required; need to be Modification of the near lane
prefabricated full-paving construction	Full lane width	60~100	Short construction time; high construction quality; only a single vertical Lower life cycle cost	High initial cost; transverse joints can easily cause damage to adjacent lanes. Impact; precast panels are easy to move under traffic loads; maintenance is difficult Difficult; need to modify adjacent lanes

3.1.2 Vehicle Equipment

At present, most of the vehicle-side equipment used in wireless charging roads is in the trial stage, and no unified standards have been formed in terms of performance, coil operating frequency, and AC conversion devices. Therefore, it is urgent to carry out standardization work and establish technical specifications recognized by the industry. From the actual situation of the current electric vehicle market, requiring automobile manufacturers to specially develop electric models adapted to wireless charging roads faces great challenges in terms of technical feasibility and commercial economy. A more feasible solution is to design the vehicle-side wireless charging device as a modular subsystem, so that it has a high degree of scalability and standardized interfaces, which can be compatible with mainstream electric vehicle models on the market, adapt to wireless charging roads of different technical standards, and retain the original performance parameters of electric vehicles. In addition, as a terminal device that consumers directly contact, the vehicle-side wireless charging device can bear part of the project cost. For example, when launching a new model of vehicle, automobile manufacturers can provide optional services for wireless charging functions on the basis of basic configuration, and through differentiated pricing strategies, achieve reasonable allocation of project costs and provide financial support for the subsequent construction and operation of wireless charging roads.

3.1.3 Long-Term Maintenance and Use

The long-term maintenance costs of wireless charging roads mainly come from the aging loss of internal electronic components and road damage caused by extreme weather conditions. Due to the complexity of wireless charging technology and the fact that core components such as internal coils are buried below the road surface, its maintenance costs are expected to be significantly higher than traditional roads. To reduce maintenance costs, a modular design concept can be adopted to assemble the internal components of the road in sections, and local replacement of faulty components can be achieved, thereby improving maintenance efficiency and reducing maintenance costs.

3.2 Comparison of the Advantages and Disadvantages of Existing Mature Charging Technologies

3.2.1 Wireless Charging Highway

Compared with traditional charging piles and other wired charging methods, wireless charging highway technology shows significant technical advantages and application potential. First, this technology breaks through the limitations of the traditional charging process on the static state of the vehicle, realizes the continuous energy replenishment of the vehicle during driving, effectively solves the mileage anxiety problem of electric vehicle users, and fundamentally expands the application scenarios and scope of electric vehicles. Secondly, wireless charging highways have the ability to charge multiple vehicles concurrently, and can provide electricity for multiple electric vehicles traveling within its coverage area at the same time. This feature has important application value in densely populated areas with a high number of electric vehicles. It can effectively alleviate the contradiction between supply and demand caused by the insufficient number of traditional charging facilities, and improve regional charging service capabilities and user experience.

3.2.2 Fast Charging Pile

Fast charging piles are the most widely used and most popular electric vehicle charging equipment, with significant technical and economic advantages. The slow charging power is usually between 3.7kW and 22kW, and is usually used for home charging. The fast charging power can reach more than 600kW and is often used for public charging. [8] It has good compatibility with the power system, low equipment unit price, and small space occupation. It can be installed and used by simply modifying the existing parking space, making it the preferred technical solution for most automobile manufacturers. However, fast charging pile technology is not perfect and still has certain limitations. First, in terms of space utilization, although a single fast charging pile occupies a small area, the use of fast charging piles requires a matching fixed parking space, and the public parking spaces on the side of urban roads cannot meet the installation requirements of fast charging piles. In large cities, parking space resources are tight, and it is impossible to guarantee that every electric vehicle user has a dedicated charging parking space. In contrast, wireless charging roads have obvious space utilization advantages and can realize dynamic charging of vehicles while driving without occupying additional parking space. In addition, in terms of cost comparison, the construction cost of a wireless charging highway should not be simply compared with hundreds of fast charging piles, but the scale effect of wireless charging highways should be comprehensively considered from the perspective of the number of vehicles served. Wireless charging highways can provide charging services for a large number of vehicles on the road, with higher utilization efficiency and service capabilities. In terms of safety, fast charging piles have certain safety hazards, and accidents such as spontaneous combustion may occur during charging, which is an inherent risk determined by the physical characteristics of the battery. Wireless charging highways use wireless charging technology, which can effectively avoid safety accidents caused by fast charging.

3.2.3 Battery Swap Station

To make up for the shortcomings of charging pile technology, battery swap stations came into being. Battery swap stations effectively solve the problem of long charging time of charging piles by replacing electric vehicle batteries. Battery swap stations include automatic battery swap equipment, spare batteries and warehouses. The construction cost of battery swap stations is much higher than that of electric vehicle charging stations. In addition, battery swap stations usually involve labor costs for equipment maintenance, which further increases operating costs [9]. China's NIO has started to apply related technologies. The number of battery compartments of NIO's fourth-gener-

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ation battery swap station has increased to 23, while the battery swap speed has increased by 22%, and the single battery swap time has been shortened to less than 3 minutes (the faster battery swap speed gives the new generation of battery swap stations a maximum service capacity of 480 times per day [10]. The operation mode of battery swap stations is similar to that of gas stations for traditional fuel vehicles, but the technology also faces many challenges. The specifications of electric vehicle batteries produced by different automobile manufacturers are not uniform, which increases the difficulty of battery management and operation. At the same time, battery storage and maintenance technology has not yet reached a mature level, and there are certain technical and management difficulties. Nevertheless, in specific scenarios such as highways, battery swap stations and wireless charging roads can form a complementary relationship, jointly improve the endurance of electric vehicles, and provide users with more convenient travel solutions.

4. Conclusion

Based on the analysis of existing research results and technology development trends, urban roads are an important breakthrough for the industrialization of dynamic wireless charging technology at this stage. In metropolitan city with scarce land resources, limited space resources cannot meet the growing demand for static charging of electric vehicles.

In this context, it is of great practical significance to transform road space into a dynamic charging carrier. By laying wireless charging facilities on urban main roads, ring roads and other traffic-intensive sections, it can not only meet the charging needs of urban electric vehicles, but also achieve efficient use of land resources. The large-scale commercial application of dynamic wireless charging roads tends to be first implemented in the traffic core areas of super-large metropolitan areas or newly planned modern cities. This is mainly attributed to the following aspects: First, the initial construction cost of wireless charging roads is much higher than that of ordinary roads. Even if future technological advances can reduce some costs, its high cost is still difficult to promote on a large scale in ordinary cities, let alone popularize in highway networks. The implementation of such projects requires local governments to have sufficient fiscal budget support, and at the same time, it is inseparable from national policy support as a pilot area for technology demonstration and promotion. Second, urban central areas usually impose traffic restrictions on heavy freight vehicles, which to a certain extent reduces the requirements for road bearing capacity and provides more relaxed conditions for the laying of wireless charging facilities. Third, super-large cities have a complete infrastructure supporting system and efficient urban management capabilities, which can effectively ensure the long-term stable operation of wireless charging roads, extend the service life of facilities, and maximize investment benefits. Fourth, the traffic flow in the core area of the city is dense, and dynamic wireless charging roads can provide charging services for a large number of electric vehicles on the road without affecting the normal traffic of vehicles, and effectively share the construction costs through large-scale applications.

In the current highway traffic system, electric vehicles are subject to the dual constraints of cruising range and charging time, and their driving range is usually limited to provincial administrative regions. When traveling long distances across provinces, fuel vehicles still dominate the long-distance transportation field because they exceed the vehicle's cruising range and charging takes a long time. In order to break through this technical bottleneck, dynamic wireless charging lanes can be planned and constructed in the highway network, and the network can be connected in series with provincial capital cities as hub nodes. In this way, electric vehicles can charge while driving during cross-provincial driving, significantly improving the effective cruising range of the vehicle. If it can be further connected with the wireless charging road network within the city, in theory, a full-scenario unlimited cruising system covering long-distance and short-distance travel can be built.

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