Review on Wireless Power Transfer in Electrified Pavements: Advancing Sustainable Urban Transportation with Magnetic Materials

Faizan Sher [1], Abuzar Khan [1], Khizar Qadeer [1], Muhammad Zafar Shah [1*], Faisal Khan[1]

[1] Department of Civil Engineering, COMSATS University Islamabad, Abbottabad Campus, Pakistan· fayzansher@gmail.com; abuzarjadoon7@gmail.com; khizarqdr10@gmail.com; zafarali@cuiatd.edu.pk faisalkhan@cuiatd.edu.pk
* Correspondence: zafarali@cuiatd.edu.pk

Abstract

Wireless Power Transfer (WPT) technology has gained renewed attention due to its potential applications in various fields, including transportation. The concept of charging electric vehicles (EVs) wirelessly has emerged as a promising solution to address the challenges associated with traditional charging infrastructure. Since electric cars (EVs) are increasingly replacing traditional gasoline-powered vehicles, it is essential to charge EVs effectively while minimizing energy loss. WPT solutions for electrified pavements show promise as a replacement for traditional charging stations. With a focus on WPT's capacity to dynamically charge moving vehicles, this analysis examines three important electric road technologies: conductive rail power transfer, pantograph line power transfer, and WPT. According to research, power transmission efficiency is greatly increased when soft magnetic composites (SMCs) are incorporated into road materials. In order to maximize the performance of WPT systems integrated into road infrastructure, this research looks at the importance of magnetic materials, namely ferrite-based composites. High prices, efficiency improvement, safety issues, electromagnetic interference, and infrastructure durability are some of the obstacles to integrating WPT onto electrified pavements. Moreover, electrified pavements encourage the use of renewable energy sources, which makes the transportation system greener and more sustainable.

Keywords: Partially magnetized pavement, Electrified Pavement, Wireless power transfer for EVs.

1. Introduction

With the development of urban infrastructure and migration from rural to urban areas, the usage of various modes of transportation, particularly passenger vehicles, has grown. This issue causes the world to face severe issues including air pollution and CO_2 emissions [1]. With the transportation sector being one of the main drivers of greenhouse gas GHG emissions globally, replacing Internal Combustion Engine (ICE) vehicles with Electric Vehicles (EV) is seen as one of the most effective approaches to achieve the goal of net-zero carbon emissions by 2050. While the shift from ICE vehicles to 50% EVs by 2030 covers a multitude of legislative and infrastructure issues, all EV producers confront considerable shared challenges in developing, producing, and maintaining the rising EV population [2].

Although electric vehicles have become very popular, there are still obstacles and restrictions preventing their broad use. These include range issues, long charging periods, the environmental impact of charging, expensive costs, and insufficient charging infrastructure. One of the most important restrictions highlighted is the range of electric automobiles. Unlike gasoline vehicles, which can travel over 600 miles on a full tank, many EVs suffer from range anxiety, which can put off potential purchasers. Furthermore, the long wait periods for charging might be inconvenient, especially in comparison to the rapid recharging of gas vehicles [3-6]. Thus, it is critical to provide the infrastructure needed for electric vehicles (EVs). One of these essential infrastructures is the charging station for electric automobiles [1]. The reduction of transportation emissions stands as crucial because these emissions function as primary agents in climate change [7]. The integration of EVs supports core sustainable development goals through promotion of cleaner technology solutions and decreased reliance on fossil fuels. Switching to electric vehicles improves public health through emission decreases while also reducing air pollution [8, 9].

2. Charging Systems

2.1. Conductive Rail Transfer

Conductive rail transfer for electric vehicles (EVs) involves the use of conductive automated connection devices (ACDs) to facilitate power transfer from infrastructure to vehicles as shown in fig 1. This method is particularly relevant for dynamic charging systems, where vehicles can charge while in motion, offering a potential solution to the limitations of static charging. Recent studies highlight various approaches to enhance efficiency, with recorded efficiencies ranging from 90.3% to 96.5% depending on the system design and operational conditions [10, 11]. Since the turn of the 20th century, buses have been effectively equipped with overhead conductive charging on city streets. In designated highway lanes, overhead conductive charging for trucks and High Duty Vehicles (HDV) is still in the experimental phase [12].

The research view on conductive rail transfer for EVs, emphasizing dynamic charging systems that allow for high-efficiency (90.3%–96.5%) in-motion charging. He highlights the historical application of buses as well as the current experimental trials for HDVs and trucks.

Figure 1. Conductive Rail Power Transfer [13].

2.2. Pantograph Line

To charge EVs using the conductive technique, as is seen in fig 2, the car and e-Road need to be physically linked. Electric trains, trams, and trolleybuses all employ pantograph lines. Electric buses and trucks are the primary applications for conductive charging, which can be done overhead (pantograph), below (road-bound), or by the side of the road, as shown in Fig2 [14, 15]. Lever constructions and movable counterweights, two recent developments in pantograph design, increase contact force with overhead lines and may increase the efficiency of energy transfer. Better power transmission performance is indirectly a result of these advances' simplification of maintenance and operating efficiency [15].

The author argues for physical connections in conductive EV charging, citing advances in pantograph design (lever structures, adjustable counterweights) that improve energy transfer efficiency, maintenance, and operating performance, particularly for buses and trucks.

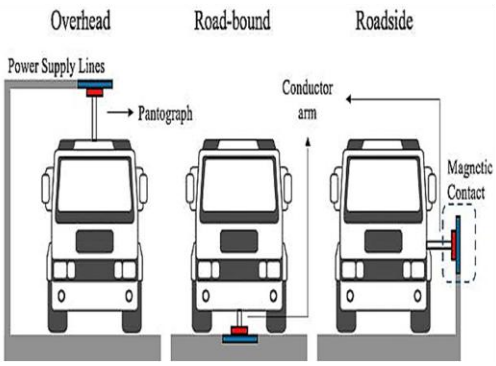

Figure 2. Pantograph Line Power Transfer [1].

2.3. Wireless Power Transfer (WPT)

As shown in Fig 3, a new technology called Dynamic Wireless Charging (DWC) enables electric vehicle (EV) batteries to be charged automatically while the vehicle is in motion. The DWC-EV can charge a battery more frequently than traditional plug-in EVs since it can be done from the road charging infrastructure while the EV is moving [16-18]. Without the need for cables or other physical connections, wireless power charging makes it possible to transfer electricity between the power source and the load [19, 20]. The Electric Road System demonstrates similar charging efficiency to traditional static chargers, achieving 96.5% in urban simulations and 95.7% in rural simulations [21].

The research emphasizes dynamic wireless charging as a solution that enables vehicles to receive electricity during operation through contact-free charging methods. The Electric Road System functions more efficiently than conventional static charging stations with efficiencies of 95.7% in rural regions and 96.5% in urban areas.

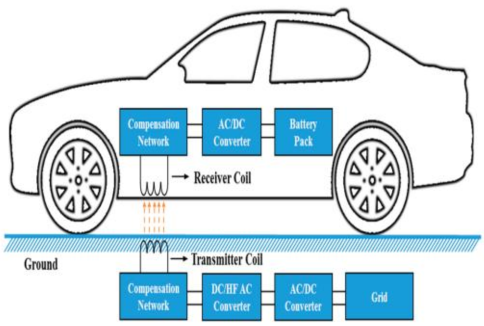

Figure 3. Wireless Power Transfer [22].

2.4. Comparative Analysis of Dynamic Charging Technology

The table 1 displays various dynamic charging technologies for electric vehicles. Buses and heavy-duty trucks are served by the conductive systems Pantograph Line and Conductive Rail, respectively. Passenger automobiles are compatible with the inductive Wireless Power Transfer system. Efficiency varies, with Wireless Power Transfer reaching 95.7% and Conductive Rail reaching up to 96.5% improvement.

Table 1: Comparison of Dynamic Charging Technologies for Electric Vehicles

Sr No.	Name	Concept	Vehicles	References
1	Conductive Rail	Conductive	Heavy Duty Vehicles	[11]
2	Pantograph Line	Conductive	Trucks and Buses	[15]
3	Wireless Power Transfer	Inductive	Passenger Cars	[23]

3. Magnetized Pavement

The reduction of vehicle emissions depends on electronic roadways because they promote electric vehicle adoption. These wireless charging systems provide continuous power while increasing user mobility since users no longer need to pause at charging locations. The integration of EV propulsion technology allows for reduced fossil fuel dependency and higher energy performance in modern transportation systems. The use of renewable energy systems to power electrified highways leads to reduced power usage and lowered CO_2 emission levels. Sustainable pavement techniques create incentives for electric vehicle adoption and push forward the development of greener urban transportation systems [7, 24].

Studies have proven that inductive charging systems allow builders to embed these systems into pavement structures to provide continuous wireless power distribution for EV vehicles while operating on the road. Through this technology EVs can receive charge once they are in motion smoothly so they become less dependent on traditional stationary charging stations [24]. Magnetic field technology remains the leading method for coil-to-coil power transfers because it delivers both convenience and safety advantages [25].

Scientific progress in conductive losses and magnetic flux leakage exists but fundamental research on road material interactions with inductive power transfer (IPT) systems remains limited. The research community primarily focuses on electrical IPT system components including conductive coils, power-electronic converters, and ferrite cores to maximize their power transfer efficiency [26].

3.1. Challenges in the Design and Implementation of Magnetized Pavements

- The performance of WPT systems is influenced by the inductance enhancement and coupling reduction factors, which vary with the magnetization properties of the pavement materials[27].

- The integrity of embedded WPT systems may also be impacted by the large vehicle loads that magnetized pavements must support [28].

- Advanced building methods and expert labor are needed to implement magnetized pavements, which can make deployment more difficult[29].

- The effectiveness of WPT systems inductive coupling is impacted by various pavement materials[27].

- The combination of electric loss from conductive networks and magnetic loss from the coatings allows for effective trapping and reduction of electromagnetic radiation[30].

3.2. Ferrite Based Magnetized Pavement

The implementation of Wireless Power Transfer technology within pavements creates a feasible charging system for electric vehicles during their motion thereby speeding up both the environmental shift and solving key transportation issues. Time-efficient EV charging and road performance enhancement is possible through the addition of ferrite materials to pavement design. The addition of ferrite powders within soft magnetic composites (SMCs) leads to substantial WPT efficiency advancements resulting in transfer efficiencies reaching 89.78%. Using soft magnetic layers in the system improves heating efficiency while minimizing power losses and steering magnetic energy in a direction that optimizes performance [31, 32].

The life cycle analysis demonstrates electrified pavements create a pathway for battery system replacement leading to sustainable transportation options [33]. However, current challenges include ensuring the long-term performance of electrified pavements and optimizing construction methods [34]. This approach also improves the accuracy of magnetic signal transmission while minimizing the physical disruption of road surfaces [35]. Integrated pavements enhance convenience for EV users by enabling wireless charging.

Studies show that combining different pavement features with additional materials helps wireless charging systems develop higher inductivity and conductivity capabilities [36]. The placement of wireless charging systems in pavement structures allows for enhanced system performance and increases the power transfer rates. Inductive charging coils should be placed correctly to provide vehicles with their best possible energy supply during movement. The well-considered implementation of road-based wireless charging systems through strategic inductive coil placement delivers better road functionality while streamlining electric vehicle integration in cities and eliminates charging-related downtime and improves accessibility [37-39].

WPT's incorporation into road infrastructure marks an important stride toward cleaner sustainable urban transportation even though ongoing work persists for better construction techniques and extended system durability. The development of electrified roadways holds a crucial future role in the global low-carbon economic transition because they enable intelligent and energy-efficient future transportation.

3.3. Comparative Analysis of Magnetized Pavement Material

Magnetized pavement materials are being explored for their potential to improve transportation infrastructure by integrating electromagnetic properties into road surfaces. These additive materials are ideal for applications like inductive charging for electric vehicles, electromagnetic shielding, and structural durability. Table 2. shows some of the additives used to improve the induction and performance properties of asphalt mixtures while increasing the electrical conductivity. These materials can also function as an electromagnetic field in pavements with IPT pads because of their conductivity. However, despite all these benefits, one should also be aware of how these materials rust when subjected to freeze-thaw cycles and attempt to employ metal additives in small or Nano sized proportions to prevent corrosion, particularly during high freeze-thaw cycles.

Table 2: Comparison of Material used in Magnetized Pavement

Sr No.	**Name of Material**	**Improvement**	**References**
1	Steel Fiber	10.46%	[40]
2	Ferrite SMC	3%	[41]
3	Mn-Zn Ferrite	1.3%	[42]
4	Nano-Magnetic	✓	[43]
5	Ferrite Powder	17%	[25]
6	Steel Slag	34%	[44]

4. Discussion

The development, integration, and optimization of wireless charging infrastructure for electric vehicles (EVs) can significantly benefit from the examination of dynamic charging technologies and magnetized pavement solutions. This discussion emphasizes how technical advancements can address critical challenges such as range anxiety, charging interruptions, and the long-term sustainability of pavements. Integrating wireless charging with magnetized pavement structures presents a promising opportunity to enable EV charging while driving.

The study highlights the potential of ferrite-based magnetic pavements in significantly enhancing the efficiency of WPT systems. By incorporating ferrite soft magnetic composites (SMCs), power transmission efficiency can be improved by up to 89.78% [32]. Additionally, conductive and magnetic modifications such as steel fiber, Mn-Zn ferrite, nano-magnetic ferrite powder, and steel slag contribute to the effectiveness of road-based charging.

While dynamic wireless charging and magnetized pavements offer promising solutions, they also present challenges including high infrastructure costs, concerns about material lifespan, and decreased energy efficiency. Standardization and legislative support are crucial for the broad adoption and long-term sustainability of these technologies. Recent studies indicate that SMC materials, such as those containing powdered Ni-Zn and Mn-Zn ferrite, have the potential to improve WPT efficiency; however, their mechanical properties need further optimization for long-term durability [42].

Research on the impact of different pavement materials on WPT efficiency remains limited, necessitating further studies to optimize material selection for enhanced inductive coupling [27]. Future developments for magnetized pavement materials may focus on exploring alternative materials, optimizing the arrangement of SMCs in pavements to enhance WPT efficiency, and adjusting the proportions of ferrite powders for improved mechanical strength and magnetic performance. Additional research should aim to improve pavement materials, material compositions, and coil alignment to enhance the longevity and efficiency of embedded wireless charging systems.

Overall, while challenges persist in optimizing construction techniques and ensuring system longevity, the integration of WPT into road infrastructure represents a significant step toward a cleaner, more sustainable future for urban mobility. As research and real-world applications progress, electrified roadways have the potential to play a pivotal role in the global transition to a low-carbon economy, ushering in a new era of intelligent, energy-efficient transportation.

5. Conclusions

Research findings show magnetic materials play an essential role to boost wireless charging effectiveness for electric vehicles (EVs). The approach has strong potential for improving transmitter-receiver coil electrical interactions that are embedded in roads which results in better charging capabilities. Optimizing the modifier percentage holds essential importance because it enables maximum effectiveness for dynamic wireless charging (DWC) systems. The seamless integration of power through electrified pavement systems increases both EV efficiency and adoption while effectively addressing range anxiety for drivers without the need for static stations. This technology scaling capability enhances its practicality for installation across different urban areas thus supporting environmental cleanliness while enabling the shift toward advanced sustainable mobility solutions.

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Abbreviations

The following abbreviations are used in this manuscript:

WPT	Wireless Power Transfer
EVs	Electric Vehicles
SMCs	Soft Magnetic Composites
ICE	Internal Combustion Engine
ACDs	Automated Connection Devices
HDV	High Duty Vehicles
DWC	Dynamic Wireless Charging
IPT	Inductive Power Transfer

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