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Review

A Review of Wireless Pavement System Based on the Inductive Power Transfer in Electric Vehicles

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Abstract: The proliferation of electric vehicles (EVs) hinges upon the availability of robust and efficient charging infrastructure, notably encompassing swift and convenient solutions. Among these, dynamic wireless charging systems have garnered substantial attention for their potential to revolutionize EV charging experiences. Inductive power transfer (IPT) systems, in particular, exhibit a promising avenue, enabling seamless wireless charging through integrated pavements for EVs. This review engages in an in-depth exploration of pertinent parameters that influence the inductivity and conductivity performance of pavements, alongside the assessment of potential damage inflicted by IPT pads. Moreover, the study delves into the realm of additive materials as a strategic approach to augment conductivity and pavement performance. In essence, the review consolidates a diverse array of studies that scrutinize IPT pad materials, coil dimensions, pavement characteristics (both static and dynamic), and adhesive properties. These studies collectively illuminate the intricate dynamics of power transfer to EVs while considering potential repercussions on pavement integrity. Furthermore, the review sheds light on the efficacy of various additive materials, including metal and nanocomposite additives with an SBS base, in amplifying both conductivity and pavement performance. The culmination of these findings underscores the pivotal role of geometry optimization for IPT pads and the strategic adaptation of aggregate and bitumen characteristics to unlock enhanced performance within wireless pavements.

Keywords: electric vehicle; pavement; inductive power transfer; asphalt mixture; concrete

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1. Introduction

With the development of urban infrastructure and immigration from rural to urban areas, the usage rate of various transportation modes, particularly passenger cars, has grown [1,2]. This issue causes the world to encounter the main problems, such as air pollution and CO_2 emission [3–5]. Therefore, the necessary infrastructures for electric vehicles (EVs) should be developed [6,7]. One of these critical infrastructures is the charging system of EVs. Researchers worldwide are trying to perform fast charging systems to reduce the time spent on EVs from 8 h up to 35 min [8,9].

In recent years, several studies have been performed on wireless power transfer (WPT) systems to provide sustainable infrastructure for EVs. These systems help a lot to charge EVs faster, leading to a reduction in battery size and EV weight and a decrease in the intensity amount of loading on road pavement. WPT can provide an impressive perspective for the sustainable development of EVs by transferring power in an electromagnetic area [10]. These systems were designed to be both stationary and dynamic [11]. IPT systems are one of the safest and the most efficient of WPT [12]. These systems, which are embedded within the road pavements, have the ability to transfer power in an air gap of 10 to 20 cm through primary coils to the receiving coils with an efficient level of 83 to 92% in EVs.

Therefore, according to the flowchart of Figure 1, in this study, we aimed to comprehensively investigate the impact of IPT pad embedment on pavement damage and explore the role of various pavement layers in facilitating efficient power transfer from the pavement to EVs. Our method involves a thorough analysis of the effects of wireless systems on pavement layers, including their response to repetitive loading and thermal fluctuations, and how these factors influence power transfer efficiency. Additionally, we will carefully examine the damage caused by the embedment of charging units on the pavement surface. Based on our findings, we will propose different methods to enhance pavement properties, ensuring the overall quality and performance of the IPT system.

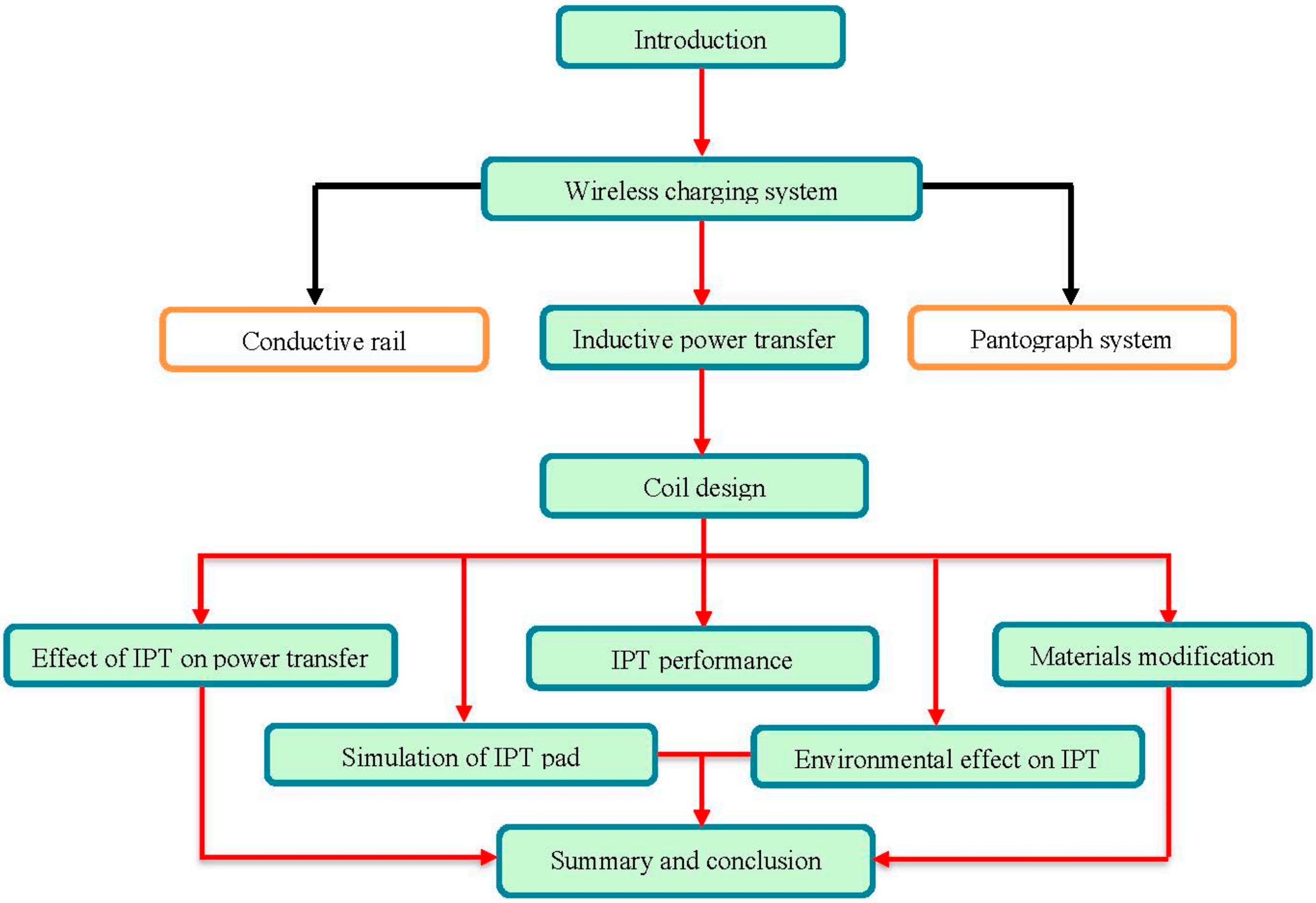

Figure 1. The structure of the present study.

2. Wireless Charging System

The charging of EVs can be operated by various methods. One of these methods is the pantograph shown in Figure 2. The power transfer in this system is fulfilled by physical contact with several weaknesses, such as charging problems in horizontal curves, creating sparks, decreasing the safety of EVs, and also causing traffic congestion due to the low level of speed while they are in charge. Another method for EV charging is a conductive rail, which can be seen in Figure 3. This method has similar problems to the pantograph. However, the third method is the wireless charging system, which has many positive aspects and provides energy without a physical connection [13].

The wireless charging system or WPT is accounted as an appropriate solution to solve EV charging problems [14]. This system provides a safe and efficient condition for EVs and also eliminates the anxiety of lack of charging and time loss of fixed charging stations worked via a plug-in [15]. As can be seen in Figure 4, in this system, unlike the plug-in charging systems, power is transferred by creating an electromagnetic condition using the embedded coils (primary coil) in the pavement to the receiver coils (secondary coil) installed under the electric vehicles [16]. There is an air gap between the embedded coils and receiver coils, which plays an essential role in transferring the amount of power. Fortunately, this system does not require human interference, and it is provided in two forms, stationery and dynamic, which can be described as follows.

In terms of configuration, WPT can be classified as either (1) stationary WPT: charge while the vehicle is not in motion; or (2) dynamic WPT: charge while the vehicle is moving along the roadway [10]. The difference between WPT systems is based on the percentage of efficiency, which is under the effect of the air gap. In other words, the smaller the air gap, the more efficient it is. Coil size is the other significant parameter in the power transfer efficiency. By studying various research worldwide, it is determined that a greater coil can transfer a high amount of power through the inductive wireless system. The system efficiency is lower for dynamic systems than for stationary charging systems, mainly because a certain amount of magnetic flux is generated by the primary coil that is not coupled with the secondary coil. Moreover, the speed of EVs plays an important role in transferring power while EVs are in motion. To put it differently, the lower speed of EVs leads to a higher charging amount of them. Last but not least are the materials of coils and the materials that surround the coil system, like aluminum or ferrite materials, which lead to creating a shield area to increase the magnetic performance.

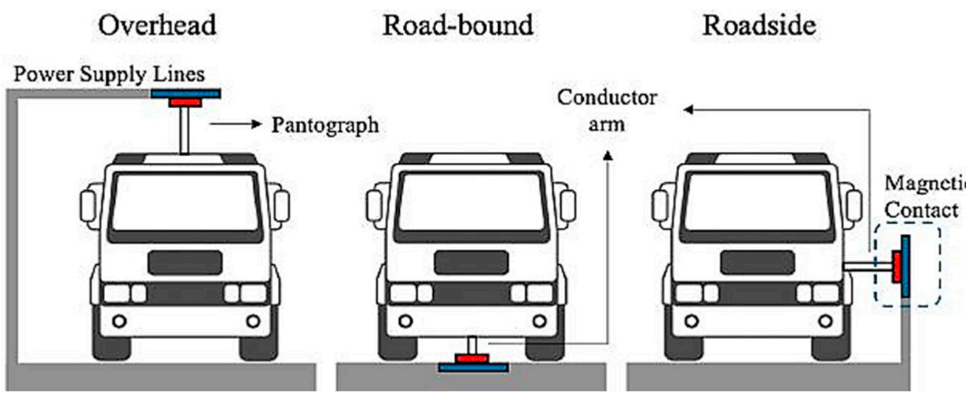

Figure 2. Electrical charging using a pantograph system [17].

One of the most important applications of wireless charging systems is related to passenger cars and heavy vehicles. In addition, they can be used in bus rapid transit (BRT) routes and decrease energy losses. These systems can decrease the size of EV batteries [18] and the delays of stopping buses for charging in stationary places, and consequently, more buses can be in service mode. Another advantage of these systems that can be mentioned is the promotion of the sales market of EVs from 2% in 2020 to 24% in 2050 [19], which not only will decrease CO_2 emissions, but will also decrease the consumption of fossil fuels [20–26]. Despite the mentioned benefits, the large-scale implementation of WPT systems can be one of the challenges for fulfilling such projects, which require a high initial investment and extensive devastating of pavements.

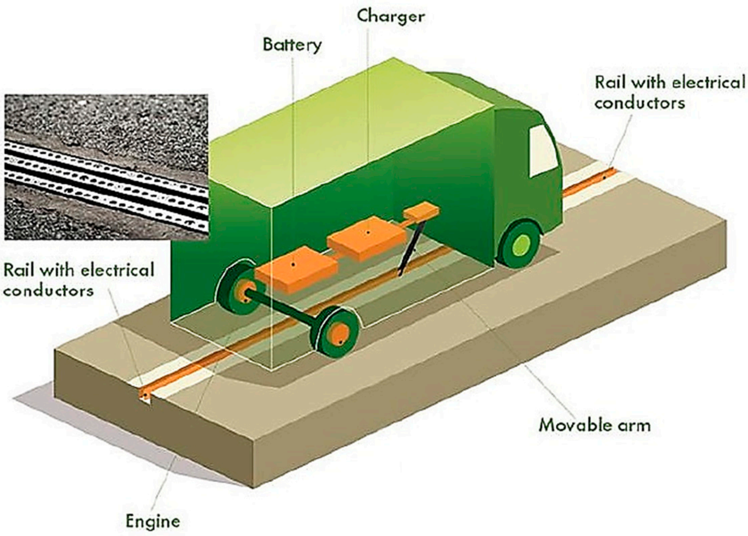

Figure 3. Electrical charging using conductive rail [13].

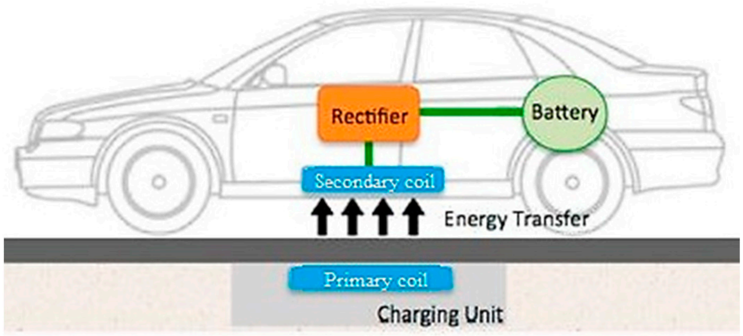

Figure 4. Wireless charging system using inductive power transfer [17].

3. Inductive Power Transfer

For wireless power transfer, various technologies exist, such as magnetic gear, capacitive, microwave, and inductive coupled charging. According to coaxial cable, magnetic gear wireless power transfer comprises two synchronized permanent magnets positioned side by side different from other wireless charging techniques. Capacitive wireless power transfer transfers power through coupled capacitors realized by metal plates. Microwave power transfer comprises a receiver installed in any low-voltage product and a microwave launcher connected to the grid. Inductive power transfer (IPT) transfers power by the use of alternating magnetic fields between primary and secondary coils. The air-core transformer with primary and secondary coils is separated through a small space and transfers power through electromagnetic induction phenomena. IPT systems have superiority and are applicable for e-roads over other mentioned systems for several reasons such as high power transfer (approximately 250 KW), high charging efficiency (71–96%), and the smallest air gap space (7.5–50 cm) [17].

IPT is a technique for coupling electrical power across an air gap without any physical contact, which was introduced over a hundred years ago. Lack of physical contact allows IPT systems to realize advantages over conductive counterparts, including resistance to environmental impacts and comfort. Over the years, various IPT systems have been presented to apply these advantages for multiple applications, such as powering bio-medical devices, powering automatic guided vehicles, and battery charging. By the utilization of IPT systems, EVs can be charged when stationary within a car park, garage, or at traffic signals, or dynamically while in motion. Robust IPT pads must be developed for installation within roadway pavements for both stationary and dynamic IPT EV charging systems to be economically viable, remaining operational for 20–30 years. Figure 5 illustrates an overview of usual IPT systems schematically. IPT systems can be divided into various modular components [27–30]:

– The power is directly derived through the power source, typically from the AC mains grid, to supply either a regulated DC supply to the inverter or a modulated AC frequency derived from the mains frequency.
– The inverter transforms this DC or extremely low frequency (LF) AC input into a greater frequency voltage and current (commonly chosen to be in the LF range of 30–300 kHz) appropriate to drive the output compensation network and magnetics that enhance the power transfer ability of IPT systems. According to standard requirements, a nominal 85 kHz is selected for EV charging systems.
– The primary and secondary pads optimize the coupled magnetic fields generated from both pads. The power is transferred through resonant IPT between the two pads. The primary pad is normally placed on or below the ground, and the secondary one is placed underneath and attached to EVs.
– A secondary controller conditions and regulates the power to the load.
– The load for an EV normally is a battery or an electric motor [30].

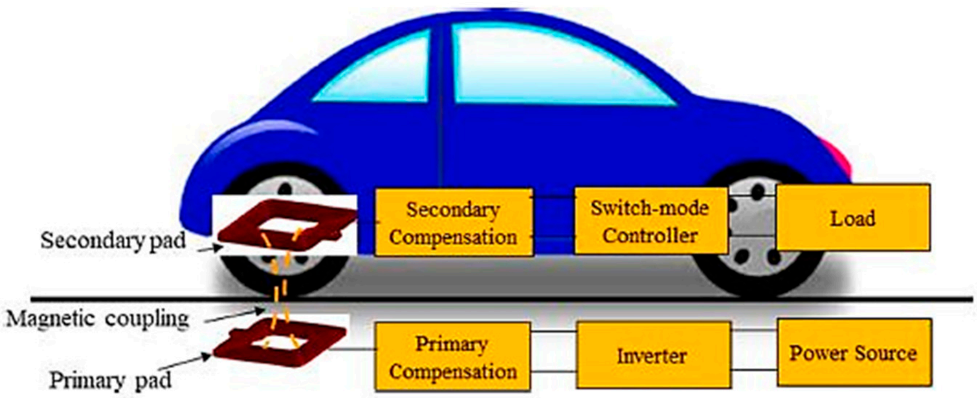

Figure 5. Overview of a typical IPT system [30].

Vehicle speed is a fundamental parameter that can directly impact the charging process in the wireless pavement system. As the speed of the EVs increases, the duration of contact between the vehicle and the IPT pads changes, affecting the power transfer rate. It is essential to investigate the relationship between vehicle speed and charging efficiency to determine the optimal speed range that ensures both effective charging and safe driving conditions [10].

4. Coil Design

As mentioned in the previous section, the coil is one of the important and inseparable components of the IPT pad, which has a role in transferring power between the energy source and receiver. Coils should have a larger dimension than the air gap (100 to 300 mm) distance between vehicles and pavement surface to operate more efficiently. Moreover, a magnetic region should be provided with various materials such as ferrite and aluminum for transferring power efficiently and conducting them to the upper layers [31]. Figure 6 shows an embedded IPT pad within the pavement with four sections: coil, ferrite layer, aluminum plate, and a case in which all details are installed [30].

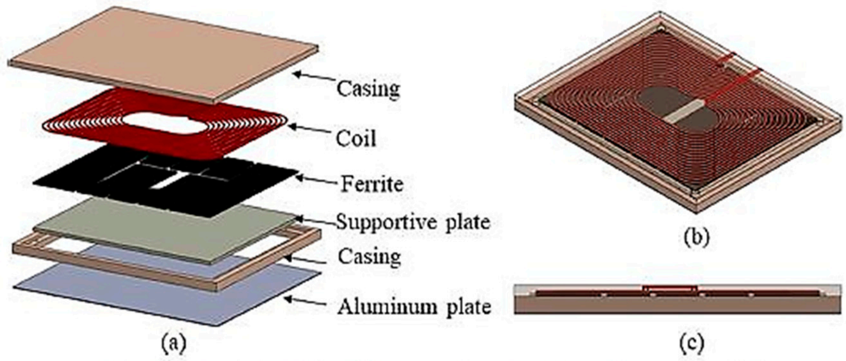

Figure 6. Embedded IPT pad with its components: (**a**) exploded view, (**b**) isometric view, (**c**) cross-section [30].

Several studies have been conducted to promote the level of coil power transfer and decrease the power loss between the pavement and EVs. In most of them, the main structure of coils and usage materials was maintained, and the difference between them is in terms of geometrical aspects. Figure 7 demonstrates different types of coils. For instance, most of the time, circular coils are used in the stationary IPT system, or DD coils can be used for compensating the energy loss, especially for pavements that encounter moisture. The DD-DDQ pad combination can achieve higher coupling and a charging zone more than five times larger in terms of coverage area than that of an equivalent circular pad system [32].

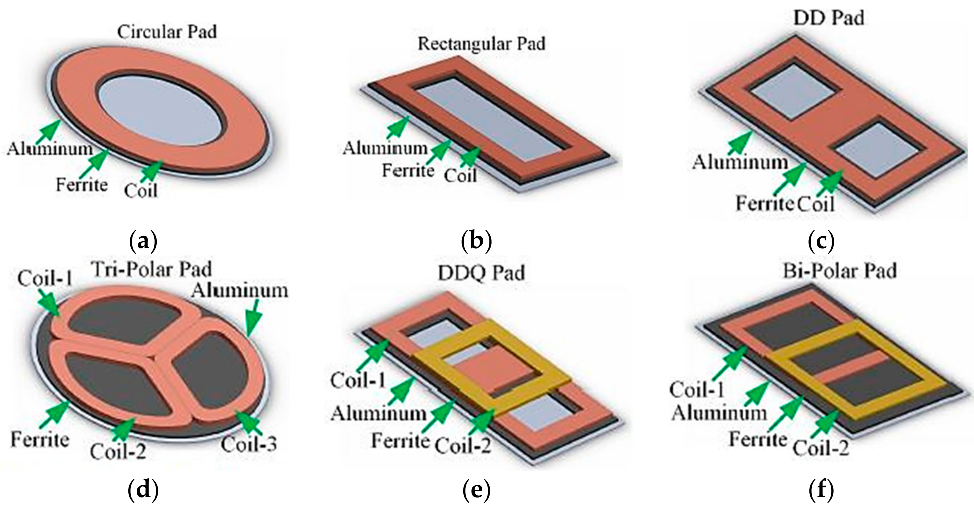

Figure 7. Different types of coil systems [30]: (**a**) Circular pad, (**b**) Rectangular pad, (**c**) DD pad, (**d**) Tri-polar pad, (**e**) DDQ pad, and (**f**) Bi-polar pad.

5. Effect of IPT Pad on Power Transfer Performance

By investigating the different studies, it was determined that various factors such as the depth of the IPT pad, materials of coils, the number of receiver coils, and factors like these have an impact on the power transfer performance of the wireless pavement. The depth of the IPT pad can be considered the thickness of the pavement as well. To put it differently, if the pavements are thicker and the IPTs are embedded in a deeper pavement layer [33], the inductivity performance and dielectric loss will be decreased and increased, respectively. In this case, the upper layer of the IPT pad is concrete, the energy loss was estimated at 3.93 w [17]. However, in the asphalt samples, this energy loss was about 0.01 w. Using materials like rubber for coil coating [17] or increasing materials like copper and ferrite for making IPT pads [34] in the amounts of 12 and 30%, respectively, can cover the weakness of power transfer of the upper layer.

If all of the above are considered, other requirements such as vehicle speed, number of receiving coils, and synchronization of the primary and secondary coils should be provided, and also if the vehicles' speeds on the wireless pavement exceed 80 km/h, the IPT efficiency will be decreased intensively. Therefore, a speed of 40 to 60 km/h can be considered an acceptable speed for efficient performance [35]. Furthermore, the simultaneity of the IPT pad and receiver coil, and the lack of deviation from each other, can decrease the energy loss [17].

Some studies have suggested two coil receivers under electric vehicles in order to solve this problem. Figure 8 shows a sample of two coil receivers. As can be seen, the connection between the primary and secondary coil was never lost, and this issue leads to an increase in the efficiency performance of the IPT pad between 96 and 100% [36].

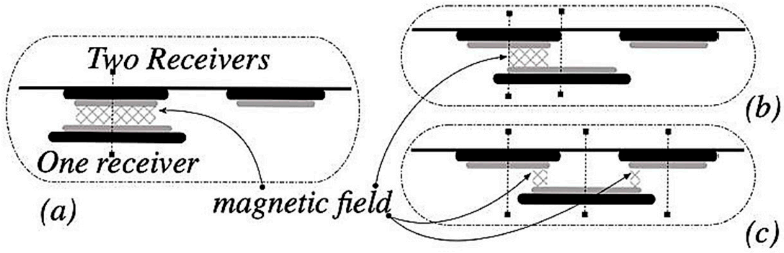

Figure 8. Two installed coils under the electric vehicle and increasing the simultaneity area between primary and secondary coils [36]: (**a**) High magnetic field, (**b**) Medium with one receiver, (**c**) Medium Magnetic field with two receivers.

The wireless pavement system (WPS) based on inductive power transfer (IPT) for electric vehicles (EVs) is undoubtedly a critical infrastructure development in the realm of sustainable transportation. While the current research has focused on various aspects of the system's design and performance, it is essential to acknowledge the potential impact of environmental factors on its stable functioning. In particular, the effects of rain, snow, and sandy soil on the WPS warrant further exploration to ensure its robustness and reliability under diverse weather and terrain conditions.

Rain and snow are common environmental challenges that wireless charging systems may encounter, especially in regions with frequent precipitation. The presence of water on the road surface can affect the efficiency of power transfer and may lead to decreased performance of the wireless pavement system. Investigating the behavior of IPT under wet conditions, analyzing the impact on charging efficiency, and developing appropriate mitigation strategies are crucial steps toward ensuring the system's consistent operation, regardless of weather conditions.

Sandy soil poses another potential challenge for the wireless pavement system. In regions with sandy or loose soil, the structural stability and adhesion of the IPT pads could be compromised. It is essential to study the interaction between the IPT pads and sandy soil, evaluating the risk of displacement or damage during operation. Addressing these concerns will lead to improved design considerations, material selection, and installation techniques, enhancing the long-term sustainability and functionality of the wireless pavement system.

6. Effect of IPT Pad on Pavement Performance

As mentioned in previous sections, IPT pads should be embedded within the pavement layers, and they should not be exposed to traffic loading. Therefore, the pavements play an important role in preventing the IPT system against thermal fluctuation, freeze–thaw cycles [37], and repetitive traffic loading [17]. Different studies have been performed on the effect of charging units (CUs) on pavement damage, and the different conditions of their performance have been evaluated.

Although pavement layers protect the IPT system, the presence of these systems causes a lot of damage to pavement layers. The significant point is that more than twice the amount of damage will be caused than to a conventional pavement layer. Various factors, including the geometry of the IPT pad, embedment depth, and their distance from each other, have an impact on the damage. Figure 9 shows the different types of damage created on the pavement surfaces affected by the embedment of CUs.

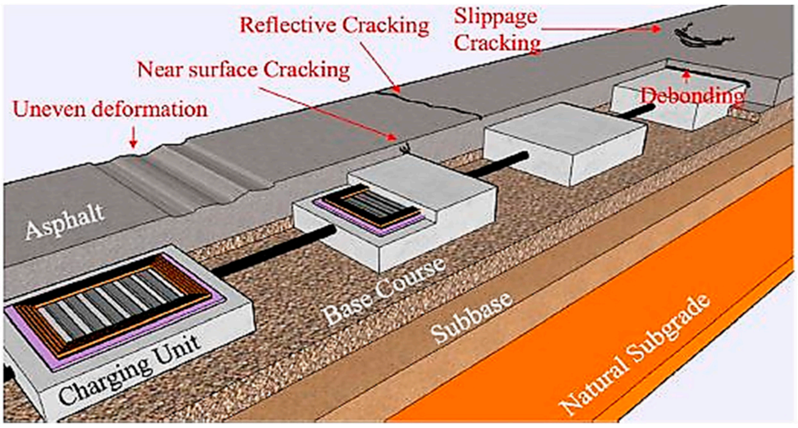

Figure 9. Damage related to the embedment of charging units in pavement [17].

As shown in Figure 9, these charging units can increase the cracks in the pavement surface and cause all kinds of damage such as debonding, slippage, and reflective cracks. These cracks and damage are aggravated at the edge of the CU and the contact surface of the pavement and the CU. Due to the fact that CUs usually are constructed from concrete, lower longitudinal strain and deformation occur exactly on the center and above the IPT surface, and the pavement faces better resistance than the CU shoulder section. In addition, debonding and slippage cracks are among the most common forms of damage in wireless pavements due to horizontal stresses caused by braking and vehicle acceleration. Reflective cracks occur as a result of CUs being closer to each other. To solve this problem, an increase in pavement thickness is suggested [17]. According to the previous section, the distance between IPT pads can be increased from each other, using two coil receivers under EVs instead.

Fatigue and rutting are among the other types of damage to wireless pavements. One of the causes of fatigue is the aluminum plate under the IPT pad, which despite the advantages such as reducing energy loss, has a negative effect on fatigue resistance. To compensate for this weakness and strengthen the electromagnetic performance of wireless pavements, it is better to use a layer of asphalt mixture containing magnetic additives. Despite the various forms of damage to the pavement due to the presence of IPT pads, rutting is one of the failures that appeared with lower intensity than conventional asphalt [8].

During the charging time of EVs on the wireless pavement, the temperature degree of the pavement reaches 87 °C, which can cause softening and thermal stresses, which contributes to other forms of damage. Therefore, bitumen should be used with a higher softening point and viscosity and lower penetration grade. Moreover, if the temperature can be controlled through different additive and bitumen modifications [38], it may be a positive point for the self-healing properties of asphalt mixtures. Otherwise, damage due to fatigue and rutting might develop [17]. The significant point is that the weight of EVs can be reduced by increasing the conductivity of asphalt mixtures and improving the coils' performance. With this measurement, the intensity of loading and damage will be decreased.

The geometry of the IPT system is one of the factors that has an impact on the damage performance of the wireless pavement. The connection areas between the CU and the asphalt experience the weakest performance against damage and the highest stress. Therefore, by rounding the shoulder of the CU with a radius of 3 to 12 cm, the intensity of the stresses on the pavement and damage can be reduced. Moreover, increasing the thickness of the pavement layer above the IPT pad can also reduce the severity of the damage [39]. However, increasing the thickness or the depth of the IPT pad can reduce the power transfer performance [40].

Dielectric properties of materials are one of the factors affecting the energy loss of wireless pavements. In other words, the presence of materials with high dielectric properties reduces power transfer in pavements. Table 1 shows the dielectric characteristic (**rε**) of different materials.

Table 1. Dielectric characteristics of different materials [41].

Materials	rε
Air	1
Water	81
Snow	6–12
Ice	4
Sand	2–6, 10–30 (wet)
Clay	2–6 (dry), 5–40 (wet)
Limestone	7 (dry), 8 (wet)
Granite	5 (dry), 7 (wet)
Asphalt	2–4 (day), 6–12 (wet)
Concrete	4–10 (day), 10–20 (wet)

As can be seen in Table 1, asphalt pavements have a lower dielectric index than concrete pavements. In other words, by implementing the asphalt pavement, more power can be transferred from the IPT pad to EVs. Among the present materials in Table 1, water has the worst dielectric performance, and in the case of moisture penetration to the pavement texture, the power transfer via the IPT pad encounters several problems [35]. Despite the lower index of asphalt mixtures than concrete, when these pavements are exposed to moisture, they experience a more noticeable decline than concrete pavement [17]. Therefore, it is better to improve the performance of asphalt pavements against moisture damage by using an ant strip additive.

7. Modification of Wireless Pavement Properties to Increase Performance and Conductivity

It is true that things like the deviation between the primary and secondary pads and the lateral movement of vehicles while driving reduce the performance of the IPT system, and by deforming the coils, part of this energy loss can be reduced, but by modifying the properties of asphalt and concrete mixtures, the efficiency of these systems can be improved by creating an electromagnetic conduction zone in the pavement. Various studies have been performed to improve the induction and performance properties of asphalt and concrete mixtures, which have tried to improve the performance of pavements against various failures by modifying the properties of bitumen, concrete, and aggregates in mixtures [42] while increasing the electrical conductivity [43]. Table 2 shows some of the additives used.

As can be seen from Table 2, these materials have mainly metallic properties and their use causes rheological changes in the properties of bitumen or changes in the characteristics of used aggregates. These changes increase the bitumen cohesion and the adhesion of bitumen (concrete) and aggregates and greatly reduce separation. In addition, due to the conductivity of these materials, they can also act as an electromagnetic field in pavements with IPT pads. But in addition to all these advantages, one should also pay attention to the rusting properties of these materials during freeze–thaw cycles and try to use metal additives in small or nano sizes so that they do not corrode, especially in high freeze–thaw cycles, as shown in Figure 10.

Figure 10. Corrosion of asphalt texture as a result of steel fiber additive [44].

Table 2. Additives used to modify inductive pavements.

Material	Optimal (%)	Test Device	Improvement (%)	Modification with	Reference
Steel wool fiber	6	ITS Electrical resistivity	15.13	Bitumen	[45]
Electric arc furnace	8	ITS, ITSM	69	Aggregate	[46]
Steel slag/steel fiber	6	Cantabro Semi-circle bending fracture Thermal constants	57	Aggregate Bitumen	[47]
Electric arc furnace	3	ITS	50	Aggregate	[48]
Steel wool fiber	N/A	Electromagnetic Induction heating	66	Bitumen	[49]
Metallic waste	4	Electrical resistivity X-ray Thermo physical	✔	Bitumen	[50]
Metallic fiber	1.5	ITS, ITSM	×	Bitumen	[44]
Waste steel shavings	10	Induction heating Electrical resistivity	✔	Aggregate	[51]
Ferrite powder	0.5	ITS Electrical resistivity	17	Limestone filler	[52]
Steel wool fiber	4	Crack-healing X-ray	✔	Bitumen	[53]
Steel fiber	10	Ice-melting	✔	N/A	[54]
Steel fibers and steel wool	10	ITS Electrical resistivity	19	Bitumen	[55]
Steel fibers	6	Induction heating Thermo physical	✔	Bitumen	[56]
Waste steel shavings	8	Heating power	✔	Bitumen	[57]
Steel wool fiber	2	Cantabro fatigue test	✔	Aggregate	[58]

Table 2. *Cont.*

Material	Optimal (%)	Test Device	Improvement (%)	Modification with	Reference
Electric arc furnace Steel slag and copper	N/A	Rutting Creep ITS	47	Aggregate	[59]
Steel fiber	6	Semi-circular bending Induction heating	✔	Bitumen	[60]
Steel wool fiber	1.5	ITS	25	Bitumen	[61]
Micron-scale steel fiber with carbon fiber	0.2	ITS Dynamic modulus	29	Bitumen	[62]
Steel fiber	N/A	Wheel tracking ITS Pull out	✔	Bitumen	[63]
Steel slag	N/A	ITS ITSM Electrical resistivity	34	Aggregate	[64]

✔: The additive materials improve the characteristics of the asphalt mixture, ×: The additive materials have a negative effect.

According to other similar studies, the addition of ferrite materials to concrete mixtures improves specimens by 50% against energy loss [65], and replacing ferrite materials with some aggregates can be suggested as a suitable solution to increase efficiency and conductivity [66]. Other studies have examined the effect of metal materials on the performance of pavements and have concluded that the addition of stainless steel wool and stainless steel fibers can reduce energy losses by up to 50% and improve the performance of pavements [8]. Also, if 1 to 20% of the weight of concrete is replaced with iron and magnetite powders, the pavement efficiency can be improved by up to 86% [67]. In addition, the type of aggregate is one of the influential parameters. Because limestone aggregates have more magnetic properties than basalt aggregates, and if the mixture is more compact, then more power can be transferred [32].

Although many researchers have suggested the construction of charging units in boxes with concrete materials [68], others believe that the creation of an asphalt pavement layer on concrete boxes causes a discontinuity between the materials [69–71]. Therefore, it is suggested that in concrete pavements, IPT pads be placed in the concrete layer, and in asphalt pavements, IPT pads be placed in the asphalt mixture to increase the cohesion and adhesion between different materials. In addition, Chen et al. proposed a method whereby if reinforced pavements such as ultra-thin white-topping pavements as represented in Figure 11 are used for the top layer of IPT pads, the weakness of pavements in energy transfer can be reduced by up to 75%, and in places that are close to the rebars, up to 85% improvement of pavement performance can be observed [72]. In another study, to improve the discontinuity between the IPT pad and its top layer, various materials such as Portland cement, polypropylene (PP), acrylonitrile butadiene styrene (ABS), XPS: polystyrene foam, stretch film, and ferrite were proposed to cover the coils [73]. The results of studies showed that cementitious materials have the highest electrical losses and have negative effects on coils. Among the materials, ABS and PP resins performed best in energy transfer.

In another study, investigators proposed a multilayer asphalt pavement system based on Figure 12, which is mostly comprised of three subsystems from top to bottom [65]: the upper part is constructed with electrically conductive layers with waste steel shavings, the middle part is an asphalt mixture layer with the pre-embedded induction coil, and the lower part is constructed with magnetically absorbing layers with waste ferrites for replacing the conventional waterproof adhesive layer. Based on Figure 13, the role of the lower part was maintaining the electromagnetic power and transferring it to the upper one.

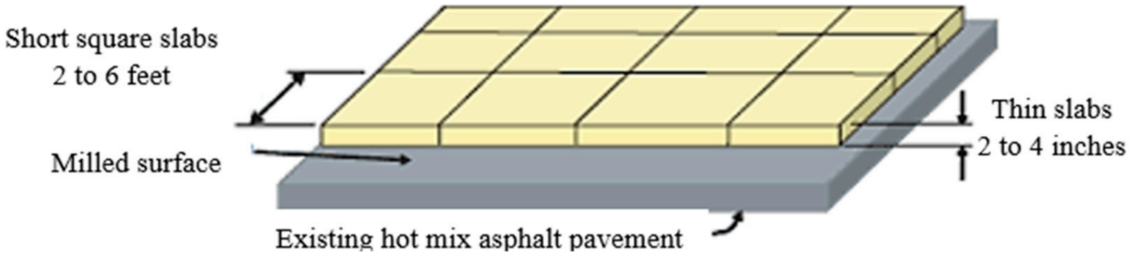

Figure 11. Ultra-thin white-topping method [73].

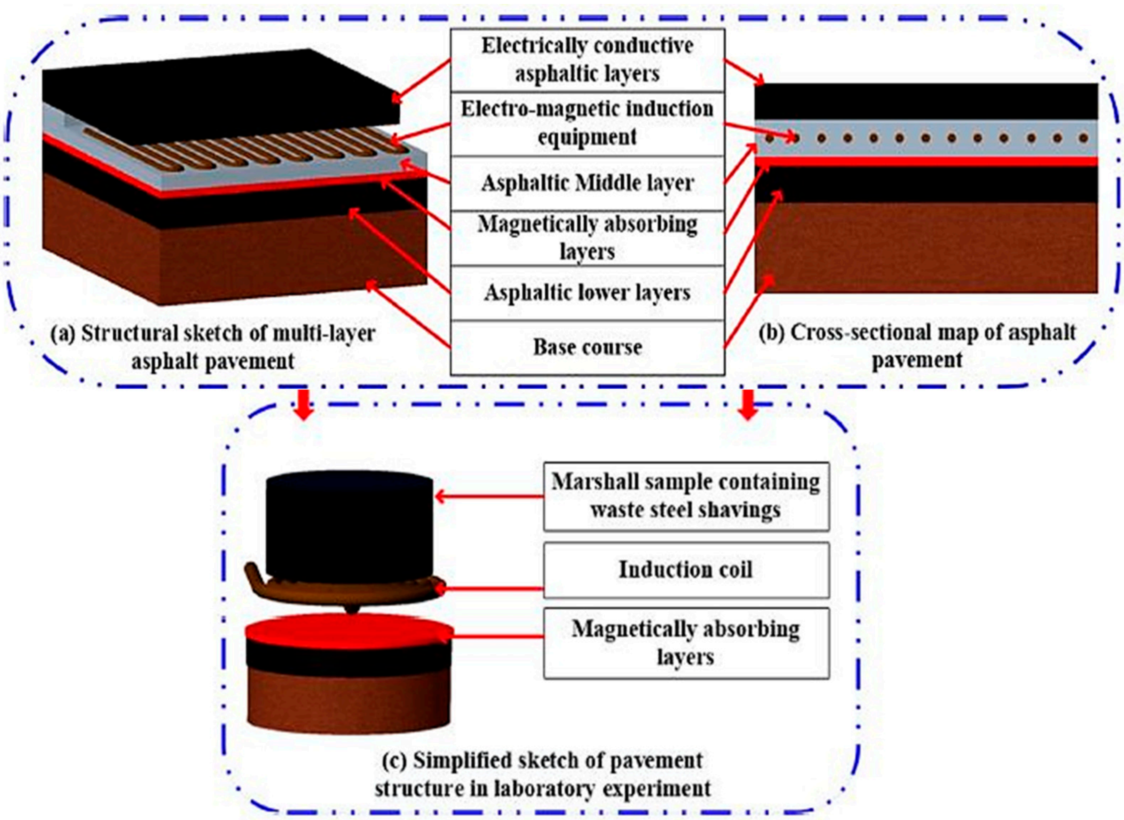

Figure 12. Structural sketch of multilayer asphalt pavements [39].

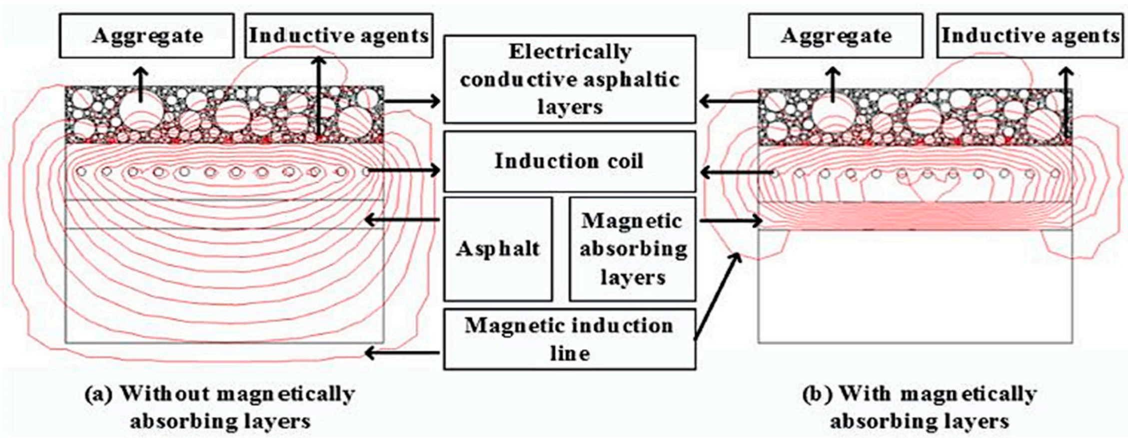

Figure 13. Magnetically absorbing principle of magnetically absorbing layer [39].

The upper layer was made with four various contents of waste steel shavings (2 to 8% by the weight of aggregates) and applied as an inductive agent in asphalts. Moreover, styrene butadiene styrene (SBS) and limestone powder were applied for the modification of bitumen properties to enhance the stability of the multilayer asphalt pavement structure. The result showed that the asphalt magnetically absorbing layers could meet the requirements of conventional waterproof adhesive layers. It was also concluded that 6% was the optimum amount of waste steel shavings. Also, the electrically conductive asphalt layer operated as the magnetic field receiving layer to achieve self-healing and deicing, and snow melting [39]. Based on previous research, nanocomposite bitumens could be applied to enhance the resistance of asphalt mixtures to moisture. These materials contain various types of nano-metal or nano-polymer composites that can simultaneously improve the performance and electrical conductivity of the mixtures.

Most studies investigated the modification of pavement with various additives as a suitable solution to improve the inductive and performance properties. However, in an innovative study, researchers suggested that a partial part of the asphalt in which the IPT pad was embedded be modified with magnetic additive (as shown in Figure 14), and other parts should remain as unmodified asphalt. This design principle creates a pathway that can better connect magnetic fields and guide magnetic flux between receiver coils and transmitter. The enhancement of wireless power transfer was also indicated for charging EVs from the partially magnetized pavement layer over the conventional pavement layer. If the embedment depth transmitter coil is 0.1 m, the wireless charging performance could be increased by 1.5% from 70% to 71.5%. However, once the thickness of the partially magnetized layer is increased to 0.4 m, the improvement rate is remarkably enhanced from 26.6 to 39.9% (by 13.3%) [8].

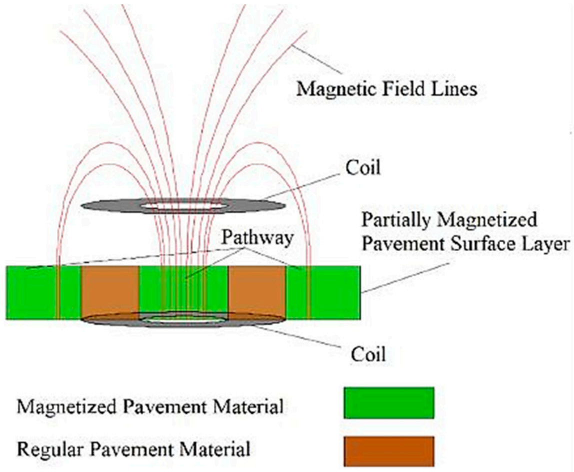

Figure 14. Design concept of partially magnetized pavement layer [8].

8. Simulation and Comparative Analysis of IPT Pad Performance

This section presents an exploration of simulation results concerning the performance of IPT pads within wireless pavement systems. Building upon empirical investigations and comparisons of experimental outcomes, this extension delves into simulation-based insights to comprehensively understand the IPT pad behavior.

Advanced electromagnetic simulation tools were employed to comprehensively assess the IPT pad performance. These simulations modeled the intricate electromagnetic interactions within the pavement structure and IPT pad configuration. Variables encompassed geometric parameters, material properties, and operational conditions for nuanced examination.

Various researchers have studied a collective perspective on IPT pad performance within wireless pavement systems. Sun et al. proposed a framework for magnetically coupled resonant wireless power transmission systems integrated within pavements. Their work highlighted the significance of resonance phenomena and optimized geometries in influencing power transfer efficiency [74]. Amirpour et al. conducted a coupled electromagnetic–thermal analysis of inductive power transfer pads within pavements.

Their research emphasized the interplay between electromagnetic efficiency and thermal effects, contributing to a comprehensive understanding of pad behavior [30]. Aghcheghloo et al. explored the influence of an emulator inductive power transfer pad on asphalt pavement temperature. Their investigation shed light on the role of emulators in simulating real-world scenarios and the resulting thermal implications [75]. Li et al. proposed a wireless power transfer-tuning model using pavement materials as transmission media. Their innovative approach investigated the potential of pavement materials to enhance power transfer efficiency [76]. Guo and Wang introduced a novel design of a partially magnetized pavement for wireless power transfer. Their work showcased the potential for improved efficiency and cost savings [8].

Integration of simulation-based insights alongside experimental results enriches the understanding of IPT pad performance. These outcomes provide a comprehensive perspective on IPT pad behavior within wireless pavement systems. By amalgamating simulation and experimental insights, contribution to wireless pavement system optimization and refinement is advanced. Figure 15 presents a comparative analysis of electrical conductivity across various simulation studies. The discernible outcome underscores the substantial influence of reinforcing the pavement materials above the Inductive Power Transfer (IPT) pad in augmenting the electrical conductivity of wireless road systems. Investigations conducted with the specific aim of enhancing this aspect [8,76] have demonstrated superior electrical conductivity when contrasted with research that primarily addresses the geometric characteristics of IPT pads [30,74].

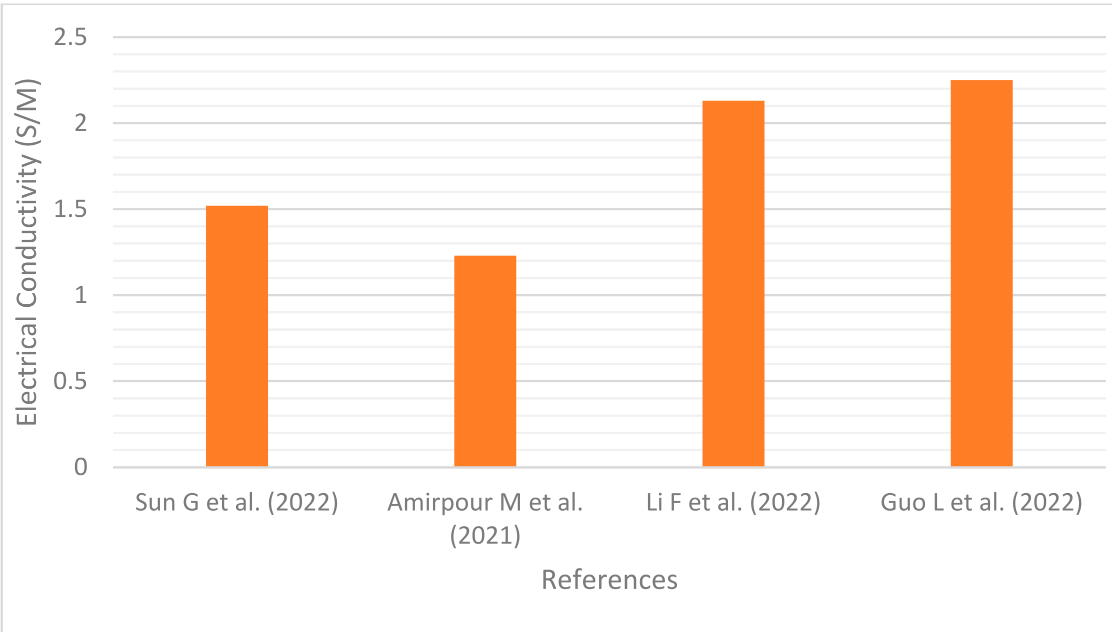

Figure 15. Comparison of simulation results in various studies [8,30,36,74].

9. Effect of Environmental Conditions on the Performance of IPT Pad

The impact of environmental conditions, such as rain and snow, on the performance of IPT systems within the context of wireless pavement charging for EVs, is a crucial aspect warranting thorough investigation. Rain and snow, being common weather conditions encountered in various geographic regions, can potentially influence the charging efficiency and stability of IPT pads integrated into road pavements.

Rainfall on road surfaces introduces moisture, which may affect the dielectric properties of the pavement material and impact the electromagnetic coupling between the IPT pads and the EV's receiving coils [77]. This alteration in electromagnetic characteristics can lead to reduced power transfer efficiency due to increased losses and impedance mismatches. The presence of water on the road surface may also impact the alignment and contact between the charging unit and the EV, affecting the overall system's performance. Addressing these challenges entails a comprehensive understanding of the interactions between water, pavement material, and electromagnetic fields, allowing for the development of strategies to mitigate efficiency loss during rainy conditions [17,78].

Similarly, snow accumulation on road pavements can pose challenges to the proper functioning of IPT systems. Snow buildup can alter the geometry of the road surface and potentially obstruct the alignment between the charging unit and the EV [17]. Additionally, snow's insulating properties can lead to further impedance mismatch and reduced power transfer efficiency [70]. Analyzing the behavior of IPT pads under snow-covered conditions and developing mechanisms for snow removal or adaptation will be instrumental in ensuring the sustained functionality of the wireless pavement charging system in snowy environments [33,76].

Understanding the influence of these environmental conditions on IPT pad performance is essential to developing a robust and reliable wireless pavement system that remains operational under various weather scenarios. By delving into these effects, we can tailor system designs, materials, and operational strategies to ensure optimal performance, thereby enhancing the overall viability and effectiveness of IPT-based wireless charging solutions for electric vehicles.

10. Discussion

The comprehensive analysis of simulation results provides valuable insights into the design, integration, and optimization of IPT pads in pavements for wireless charging of electric vehicles. Each finding holds significant implications for the development of sustainable and effective charging infrastructure. We have discussed the results in detail and their potential impact on the future of wireless power transfer systems and pavement design.

The geometry of the charging unit emerged as a critical factor influencing tension and damage in the pavement. Creating fillet-shaped shoulders with a radius of 3 to 12 cm was found to be an effective strategy to reduce tension and mitigate any potential damage. This highlights the importance of optimizing IPT pad design to ensure minimal adverse effects on pavement integrity and longevity. Further research in this area could explore alternative geometrical configurations to identify the most pavement-friendly charging unit design.

The close application of primary pads within the pavement resulted in the expansion of cracks on the pavement surface. To address this issue, we propose increasing the number of receiving coils under electric vehicles, which significantly enhances charging efficiency by 96 to 100%. This finding underscores the need for precise coil placement and distribution to ensure reliable power transfer while minimizing pavement damage. Future studies could focus on dynamic coil reconfiguration strategies to further improve charging efficiency and reduce potential pavement impacts [79].

Furthermore, the presence of an aluminum plate under IPT pads was found to cause fatigue damage in pavements. To improve pavement induction capability and reduce fatigue damage, we recommend substituting aluminum plates with modified asphalt mixtures containing metal and magnetic additives. This finding highlights the potential of advanced materials to enhance pavement performance under the influence of charging infrastructure. Further research could explore the durability and performance of these modified asphalt mixtures under various loading and environmental conditions.

To address reflective crack formation, we suggest increasing the thickness of the upper layer of IPT pads and modifying aggregate and bitumen with suitable additives. This approach reduces the intensity of reflective cracks and improves the long-term performance of pavements. The importance of pavement composition and construction in preventing reflective cracking is evident, and further investigations could explore innovative materials and construction techniques to mitigate this type of pavement damage [80,81].

Proper integration and alignment of charging infrastructure with the underlying pavement structure is essential to prevent longitudinal strains and pavement deformation. Embedding IPT pads within a case similar to the upper layer is recommended. In concrete pavements, IPT pads should be embedded within the concrete layer, while in asphalt pavements, IPT pads should be embedded within the asphalt layers. This finding highlights the significance of optimal charging unit integration to maintain pavement integrity and durability. Future research could explore dynamic behavior under the presence of embedded charging units to optimize pavement design and performance.

Lastly, the study's suggestion to modify asphalt mixtures with metal additives or nanocomposites based on SBS bitumen opens possibilities for enhancing the self-healing ability and inductivity of pavements. These modifications improve pavement performance against various types of damage such as fatigue, rutting, and moisture susceptibility. Further investigations could delve into the precise mechanisms and long-term behavior of these modified asphalt mixtures to optimize their composition and performance [82–84]. Also, various statistical analyses, machine learning, and optimization methods can be applied for further investigation [85–98].

This comprehensive discussion of simulation results offers valuable insights into the design, integration, and optimization of IPT pads in pavements for wireless charging of electric vehicles. The findings underscore the importance of thoughtful charging unit design, precise coil placement, and pavement materials to achieve efficient power transfer while minimizing pavement damage. The implications of this research have significant relevance for the development of sustainable and effective wireless charging infrastructure, promoting the growth of electric vehicles in the future.

11. Conclusions

Our study focused on investigating the impact of inductive power transfer (IPT) pads on pavement inductivity, conductivity, and durability. Through the exploration of various wireless power transfer systems, IPT pads emerged as a safe and efficient charging solution due to their geometry-sensitive power transfer efficiency. Our investigation revealed several key insights into the effects of IPT pads on pavements. Optimizing the geometry of charging units, particularly by implementing filleted shoulders, mitigated tension and damage in pavements. We also found that embedding more receiving coils under electric vehicles improved charging efficiency and reduced pavement cracks, while modified asphalt mixtures with additives enhanced induction capability and reduced fatigue damage. Furthermore, we underscored the significance of modifying asphalt mixtures with metal additives and nanocomposites based on SBS bitumen to improve pavement performance against various forms of damage. The integration of IPT pads with pavements offers a sustainable charging infrastructure for electric vehicles. However, challenges and considerations remain for its widespread adoption:

1. Scalability and Infrastructure: The scalability of the system to accommodate a growing number of EVs is crucial. A robust and scalable WPS infrastructure is necessary for simultaneous and efficient charging in urban and rural areas.
2. Standardization and Interoperability: Establishing industry-wide guidelines and protocols is essential to ensure compatibility between different EVs and WPS implementations.
3. Environmental Impact: A comprehensive life cycle assessment is needed to evaluate and minimize the ecological footprint of IPT technology.
4. Integration with Smart Grids: Integrating IPT with smart grids can optimize energy management, contribute to grid stability, and support renewable energy integration.
5. Cost-effectiveness: Research efforts should focus on developing cost-efficient materials, processes, and installation techniques to make the technology economically viable.
6. Public Awareness: Collaborative efforts involving stakeholders and the public are essential to promote the adoption of IPT technology.

In summary, our study sheds light on the potential of IPT pads to revolutionize EV charging infrastructure. While challenges exist, addressing them will pave the way for a sustainable and efficient transportation future.

Looking ahead, the integration of IPT into pavements heralds a revolutionary shift in EV charging and urban infrastructure. Autonomous fleets, dynamic charging, grid synergy, and urban planning integration present a horizon of possibilities. By fostering innovation, collaboration, and sustainable practices, IPT-equipped pavements hold the promise of shaping a greener, smarter, and more efficient transportation landscape.

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