ELECTRIFICATION OF ROADS: INFRASTRUCTURAL ASPECT

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ABSTRACT
Considering the environmental impacts of traditional vehicles regarding emission and use of fossil fuel, Electrical Vehicles (EVs) have become a potential solution for enhancing the sustainability of road transportation sector. In this, the establishment of ‘Electrified Road’ (E-Road) infrastructure network that allowing for charging EVs conveniently has been given focus to reduce restraints from the battery. Being used as a contactless charging solution, the Inductive Power Transfer (IPT) technology is given as the technical base of E-Road in this paper. Firstly, a brief introduction about the IPT charging system is made, together with the associated pilot efforts towards the application in a dynamic way. Thereafter, from a road infrastructure point of view, the challenge for the infrastructure aspect i.e. the integration of charging facilities into the road pavement and its long term maintenance management are discussed. The authors want to warn the developers in this field to be more aware of the infrastructural aspect since the final success of implementing the E-Road into practice needs not only the charging technologies but also cross-coupling efforts from like road infrastructure.

Keywords: Electrification, Road infrastructure, Inductive charging technology, Maintenance
1 INTRODUCTION

To move the sustainability development in road transportation sector forward, short-term activities can promote improvement in fuel efficiency and vehicle emission controls while the long-term goal is to transfer from fossil-based energy source to other renewable resources. As an alternative solution, Electrical Vehicles (EVs) have been given focus as a potential solution towards enhanced sustainability of the road transportation sector in the long term, given the reported zero tailpipe emission and high energy efficiency. In this, due to the limitations of energy source technologies, recharging opportunities away from home has become a critical concern to achieve widespread demand for the use of EVs. The European Roadmap (2012) (1) has also pointed out that the electrification of road transport must be accompanied by an adequate electric infrastructure development.

1.1 Definitions

In this paper, the ‘Electrified Road’ (E-Road) Infrastructure is defined as a transportation infrastructure that is able to “deliver the electrical power to charge EVs efficiently stationary or even in motion, using specific conductive or contactless charging systems”. Within this definition, E-Road can serve as an ordinary road for vehicles driving on and at the same time delivering electrical energy to power EVs (refer in particular the EVs that use batteries). In this sense, the charging system is the functional component that will be enabled from the road matrix in an E-Road. Currently, two charging methods in both stationary and dynamic ways have been found developed towards the application: i) Conductive Charging. Stationary conductive charging way is to use a cable to plug into a car by hand and has been commonly seen in existing EV charging infrastructures. For dynamic conductive charging, different ‘pantograph’ connections have been tried with the aim to deliver power from overhead electrical cables or the conductive track that mounted on the road surface. ii) Contactless Charging. This method refers to use the Wireless Power Transmission (WPT) system to deliver electrical energy to the EV at a gap distance stationary or dynamically. The contactless charging solution was developed later than conductive solution but indicates more convenient and possible safer characteristics, so as to be regarded as an ultimate solution. Being a near-field WPT technology, the Inductive Power Transfer (IPT) charging technology has shown good performance and is being studied actively as a contactless charging solution, which is therefore given as the technical base in this paper.

1.2 Motivation and scope of this paper

The success of the E-Road infrastructure not only relies on the technologies allowing for charging action, but also their appropriate integration into the road structure and the good functionality in the long service lifetime. Compared to the active studies over the charging technologies, little attention has been found yet given to the practical road infrastructure where the charging solution will be enabled. In a road infrastructure point of view, a successful implementation of integrating the charging facilities into the road pavement can be of considerably challenging, e.g., the standard construction and maintenance procedures, the road material recycling principles utilized today may be in need of severe modifications. Hence, the content of this paper is organized as follow: 1) A brief introduction of the IPT charging technology and a survey over the past efforts dedicated to pilot infrastructure are made. 2) In a road infrastructure point of view, the challenges to the E-road infrastructure towards good long term performance are discussed and some general recommendations are given. This is just a start point of the research in this multidisciplinary research domain and more practical research efforts are needed in future.
2 BRIEF REVIEW OVER THE IPT CHARGING TECHNOLOGY AND THE PILOT EFFORTS

2.1 IPT charging system
A typical IPT system usually consists of an on-board device installed under the vehicle’s chassis and an off-board power delivery device mounted on the road surface. As illustrated in FIGURE 1, a stationary IPT off-board system that will be integrated into the road surface mainly has three parts typically: 1) the power supplier provides a DC output voltage by a rectifier; 2) a converter to achieve high output frequencies (normally between 20kHz~100kHz), combined with a capacitance to achieve resonance and reduce the switching loss; 3) a transmitter consisting of coils, ferrite cores and backing plate, which is mutually coupled with the pick-up device. The on-board part can pick up high frequency AC current through magnetic coupling and change into DC current to charge the installed battery.

![Diagram of a typical stationary IPT system for EVs](image)

FIGURE 1 Diagram of a typical stationary IPT system for EVs

The main restraints for an IPT charging system are the limited energy transfer distance and transfer efficiency. Different configurations of the transmitter (usually includes conductive coils, ferrite cores and backing plates) have been studied with the aim to improve the system’s performance in these aspects. According to the studies (2, 3, 4, 5 and 6), circular shape structure (FIGURE 2 (a)) has been studied actively as the layout of charging transmitter in stationary IPT system, while new polarized and double polarized structures (FIGURE 2 (b) and (c) respectively) suggest better tolerance for gap distance and misalignments. For a dynamic off-board IPT system, the geometry can be the successive placement of above monomers, while long or sectioned wire-loops structure and ultra slim bone structure (shown in FIGURE 2 (d)) have also been found used (7-11).

![Schematic of different transmitter’s configurations in IPT Off-board systems](image)
2.2 A survey on the E-road pilots

The pilot test of IPT charging system in a dynamic way can date back to the project organized by California Partners for Advanced Transit and Highways (PATH) in the period of 1980s~1990s (12). The cross section geometry of the IPT charging roadway in the project is shown in FIGURE 3. In this, an epoxy/sand/fiberglass approach was employed to fabricate the inductor modules, which were embedded into the pavement as entirety. It was reported that mechanical integrity problems were immediately induced after the construction. During the installation of conductors, they attempted to seal the conductor slots with clay but the clay entered the vaults. In many locations, the seal was inadequate because the polyester leaked through the seal into the vault, leaving sand with a thin film of polyester coating the individual grains and air-rather than polyester-filling the remaining volume. Hence, these areas were very weak and cracks developed shortly after being exposed to traffic. Polyester rather than epoxy as the resin mixed with sand was used for potting the conductors in place; thus, the polyester and aluminum in the slot expand much upon heating (primarily solar loading), causing cracking along both edges of the conductor slots. Furthermore, due to the thermal expansion discontinuities around the potting compounds, the cables buckled seriously and caused the most severe failure of the mechanical integrity of the roadway.

FIGURE 3 Illustration of roadway and pickup inductor cross section geometry (after PATH, (12))

In recent years, many pilot cases were found actively investigating the feasibility of the IPT charging system. However, the considerations regarding the infrastructural aspect in these pilots are limited while a few are described as follow.

- **KAIST’s OLEV project** (in South Korean, (13)): The existing road lane was firstly excavated, and then the cable conductors and ferrite cores were installed. These conductors and ferrite cores were sealed by cement concrete then and a thin asphalt overlay was applied finally. In this, no inductor module were used when compared to the PATH’s way.

- **Flanders’ DRIVE project** (in Belgium, (14)): The total test track length is 600 meters, which include two inductive sections. In this, section 1 used the cement concrete pavement and section 2 used the asphalt concrete pavement. They claimed that it is possible to integrate the system into both concrete and asphalt road surface but tolerances hint towards prefabricated modules.
- **Slide-in Electric Road System-Inductive project** (in Sweden, (15)): The test track facility has got a total length of 300 m of which 4 highway segments of 20 m have been built. Firstly, the top 200 mm of asphalt road surface were ground away in a strip 800 mm wide. Then, the 20 m primary winding segments are installed in a carrier to maintain the winding shape, while the carrier is fixed to the roadbed and the cable ends routed to the wayside power converter. Finally, 40 mm asphalt is applied to complete the segments installation. One must notice that ferrite core is not used in this pilot.

It can be seen that little research has been found regarding the protection of charging facilities and also road structure from traffic and environmental loading damages. In addition, the construction is also without taking into consideration and there is lack of basic requirements, e.g., whether the charging facilities are better integrated directly into the road pavement or firstly prefabricated in a module as an entirety.

### 3 THE SUCCESS FOR E-ROAD INFRASTRUCTURE

C. Grant et al (2013) in (16) have already pointed out the problem areas to be solved for IPT solution are the development of appropriate roadway infrastructure, e.g., the fragile ferrite materials have to be integrated into the road pavement to give a long service life in a very hostile environment (considering the mechanical and environmental loading). In fact, not only the protection of the fragile IPT facilities is important, the protection of the road structure is also essential. If E-roads are damaged during their designed service lifetime, it can also affect the IPT systems from functioning properly, leaving the E-Road in a malfunction situation. A schematic illustration of a potential E-Road structure is shown in FIGURE 4.

![FIGURE 4 Schematic illustration of a potential E-Road structure](image)

It is just a start point of research in this domain and many problems can challenge the success of E-Road infrastructure. Given the uncertainty of the geometry and material properties of charging facilities, they are assumed to be integrated into the existing pavement as an entirety. Hence, the attention in this paper is mainly given to the structural performance of this ‘composite road’. In the following the HMA overlay composite structure is discussed as an example to illustrate the importance and the difficulty for the structural integrity of E-Road. Thereafter, some potential approaches that may contribute to the structural integrity improvement are summarized. Moreover, the maintenance management in the long term run is also given focus.
3.1 The complex E-Road structure
Due to the structural and material deteriorations caused by the traffic and environmental loading, distresses in the form like cracking and rutting can develop gradually during a road’s service lifetime. Theories and models are available to predict these distresses in current pavement design framework, however, their implementation for composite road structures can be perceived as difficult. For instance, Hot Mix Asphalt (HMA) overlay to be placed over the existing Portland Cement Concrete (PCC) pavement is a typical composite pavement structure, which is also taken as a popular cost-effective rehabilitation method. Due to environmental and traffic loading, reflective cracking (the primary distress mode for this kind of structure) can be induced around the joints between two PCC slabs. The complex mechanical and thermal responses inside this kind of composite structure are difficult to be predicted, which can be illustrated by the complex reflective cracking mechanisms that shown in FIGURE 5. Similarly, given the presence of the charging facilities, unexpected deformations or cracks can be induced inside E-Road structure as a result of the traffic and environmental loading. The immediate impact is that the E-Road structure will experience premature damages in early lifetime, and the malfunction of the whole infrastructure can be the result.

FIGURE 5 Schematic of reflective cracking mechanisms due to (a) traffic loading and (b) temperature variations (after Lytton (17), and Mukhtar, et.al (18))

3.2 Approaches to improve E-Road structural integrity
As described above, little knowledge over this kind of composite structure is available. One similar case can be found is the ‘solar energy harvesting road system’ pilot research performed by the Research & Development department of Ooms Avenhorn Holding (The Netherlands) (19, 20). In this project, polypropylene pipes with 30mm external diameter were embedded inside the road pavement and with a 100mm spatial distance between each other. The study on the structural effect of this road energy system to pavement performance suggests that if the pipes are located at a depth lower than 50mm, damages can be expected in asphalt mixtures due to the loading. Likewise, permanent deformation or shear failure of the asphalt around the discontinuities may happen because of the peak stresses near the tube. They also concluded it can be effective to delay these premature damages by a mixed utilization of reinforcing grids, high quality polymer modified asphalt materials, and interface layers. In E-Road situation, similar
mechanical risks can exist, especially at the interfaces between the IPT facilities and road materials. In the following some potential technologies that may have the opportunity to improve the E-Road structure integrity are summarized.

3.2.1 Overlay system
An extra thin overlay with good functionality on the E-road surface may be useful and the potential benefits can include the following aspects:
- The IPT facilities can be protected against accidental traffic or environmental loading damages, and also water intrusion.
- An overlay may act as a stress relief layer to improve mechanical integrity and benefit the E-road’s long term performance.
- The maintenance and rehabilitation activities can be confined to only the overlay provided no structural failure happens, which can be cost-effective.
- The safety issues relating to high voltage can be avoided.

A brief summary regarding the use of available overlay systems is shown in TABLE 1. However, their real effectiveness to improve E-Road long term service performance should be investigated carefully before implementation; otherwise, damages in the form like reflective cracking can be expected. Meanwhile, an extra overlay can increase the energy transfer distance (2~5cm), which can potentially influence the charging power and efficiency.

3.2.2 Joint system and interlayer system
Joint system can accommodate very large structural movements, so the application has been found, e.g. between asphalt sections on road bridges. For instance, polymer-modified asphaltic plug joints (APJ) in (21) are required to work within a temperature range from -25°C to +45°C and to sustain gap closings and openings from -12.5mm to 25mm, at the same time be able to take vertical gap movements up to a maximum of 5mm. Interlayer system in different types have been used a lot to control reflective cracking and preserve the integrity of the pavement. For instance, the Asphalt Rubber Membrane Interlayer (ARMI) can help reduce the stress concentrations while its structural thickness can reduce deflections and also moisture (22). Other interlayer systems, e.g., geosynthetics and reinforcement interlayers also have the potential to improve the structural integrity of the pavement. A brief summary of these technologies is given in TABLE 1.

In summary, the use of above systems can facilitate to improve E-Road structural integrity and prevent premature damages. However, these systems are not likely to be effective by applying directly i.e. modifications are required for E-Road because of the changed structure and material properties.
## TABLE 1 A summary of potential methods for improving E-Road structural integrity

<table>
<thead>
<tr>
<th>Method</th>
<th>Mechanism</th>
<th>Materials</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overlay systems</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Asphalt mixture overlay</td>
<td>Increased thickness (23)</td>
<td>To retard reflective cracking by increasing the thickness of HMA overlay.</td>
<td>Not applicable</td>
</tr>
<tr>
<td></td>
<td>Reinforced HMA materials (24,25)</td>
<td>To provide greater resistance to stresses by reinforcing the pavement materials.</td>
<td>Polymers modified bitumen (SBS, rubber, carbon black, etc.), short-length (polypropylene or polyester) fibres.</td>
</tr>
<tr>
<td></td>
<td>Open graded structure (26,27)</td>
<td>Contains large inter-connecting air voids and can relieve the stresses caused by PCC movements.</td>
<td>Open gradation asphalt mixtures, e.g., SMA and OGFC.</td>
</tr>
<tr>
<td></td>
<td>Surface seals (28)</td>
<td>Be applied before the road surface deteriorates to the stage patching or reconstruction is required.</td>
<td>Hot bitumen or cold bitumen emulsion is sprayed onto the road surface, followed by spreading qualified aggregate chips.</td>
</tr>
<tr>
<td></td>
<td>Slurry Seals (28)</td>
<td>Be applied in thin overlays (varies from 3 mm to 20 mm) to avoid permanent deformation caused by the traffic.</td>
<td>Mixtures of bitumen emulsion, fine aggregates, filler, water and specific additives.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Extending the life of existing pavements by protecting them against ageing and the environment, but do not contribute to the structural strength of the pavement.</td>
</tr>
<tr>
<td><strong>Closed Joint systems</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Joint materials (21, 29, 30)</td>
<td>Be placed between two pavements to accommodate movements, improving waterproofing, riding quality, noise reduction.</td>
<td>coal-tar products, rubber, silicone, and polymer modified asphalt binder.</td>
</tr>
<tr>
<td></td>
<td>Geometry design (29, 31, 32)</td>
<td>To optimize gap plate width, thickness, edge geometry and the interface geometry.</td>
<td>Not applicable</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Can help reduce the interface stresses or the tensile stresses within the joint materials.</td>
</tr>
<tr>
<td><strong>Interlayer systems</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Stress absorbing membrane interlayer (22, 33, 34)</td>
<td>Absorb movements at the joints and dissipate stress before it reaches the overlay.</td>
<td>Placing a seal coat made of rubber asphalt binder then rolling in coarse aggregate chips.</td>
</tr>
<tr>
<td></td>
<td>Geosynthetics interlayers (17, 34, 35, 36, 37)</td>
<td>Use fabrics, grids, and composites to reinforce the HMA overlay, and impregnated in tack coat to absorb excessive stresses.</td>
<td>Geotextile, fiber-glass, geocomposite, etc. tack coat is emulsified and rubberized asphalt.</td>
</tr>
<tr>
<td></td>
<td>Reinforcement interlayers (38, 39, 40)</td>
<td>To reinforce overlay in the event of excessive yielding or fracture of interlayer.</td>
<td>Steel nettings, Glass-fibre grids.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Initial high cost of construction but can extend lifespan longer.</td>
</tr>
</tbody>
</table>
3.3 E-Road long term maintenance management

Normally, the aim of pavement maintenance activities is to extend the road service lifetime and make users safe and feel comfortable. The maintenance management for E-road infrastructure during its long service lifetime will also be confronted with some practical challenges. In order to ensure the optimum functionality of E-Road for a very long time, the following considerations regarding E-Road maintenance management can become important.

3.3.1 Continuously monitoring of E-Road structure

In a normal pavement management system, pavement condition surveys over e.g. deflection, roughness, cracks are carried out periodically, based on which the impending distress can be assessed and the future deterioration can be prevented to delay large rehabilitation actions. Different from normal pavement condition surveys which only record the distresses that have already appeared, it is important to detect damages inside the E-road in a very early stage, while the failure may cause irreversible distresses and increase maintenance cost or even shorten the lifetime. The continuous structure health monitoring system can be adapted to do so through timely monitoring the strain, stress and temperature variations inside the pavement. In this, different kinds of sensors (with cables or wireless) are available to be utilized by the monitoring system, the selection of which in E-Road situation should consider carefully over aspects like electromagnetic noise immunity, measurement accuracy (especially around discontinuous interfaces) and structural integrity with the E-Road.

3.3.2 Maintenance activities

According to AASHTO (41), the maintenance of a pavement includes: i) periodic maintenance activities to preserve the existing pavement conditions, and ii) major rehabilitation activities i.e. resurfacing, restoration, rehabilitation and reconstruction. Due to the sensitivity of the IPT system to the energy transfer distance and spatial misalignments, the requirement for E-road surface quality could be much stricter than normal pavements. Hence, the periodic maintenance activities can be important and the preventive maintenance can be focused. The preventive maintenance is carried out when the road is still in good condition to delay the potential surface failures, which includes activities like sealing the pavement surface and controlling the effects of oxidation, ravelling and surface cracking (42). In addition, resurfacing of the overlay can be done every several years to ensure the protection functionality, safety and comfort. Given the complex structure of E-Road and high initial cost, the major rehabilitation activities should be delayed as long as possible; if inevitable in future, they are better to be limited to the road material section rather than the whole structure. This can be one of the reasons why the facilities are better envisaged to be prefabricated in the module and embedded as an entirety. Moreover, the influence to the functionality of E-Road infrastructure by extreme climatic conditions (e.g., winter freezing and spring thawing) is unclear at the moment.

4 CONCLUSIONS AND RECOMMENDATIONS

Today, large-scale deployment of different EVs charging infrastructures is still in its early stages; likewise, almost all road infrastructures built and maintained are still based on the traditional building principles which are not necessarily catering towards the use of electrical vehicles. From a road infrastructure perspective, this paper tried to investigate the potential challenges that have not been taken into account for the success of E-Road infrastructure. The conclusions and some general recommendations are given as follow:
Different charging solutions have been under investigation as options for the future EVs’ charging infrastructure. In this, the Inductive Power Transfer technology has shown good characteristics and studied actively as used in the contactless charging solution. The survey performed over the E-Road pilots shows that most pilot efforts have been given to assess the performance of the charging systems, whereas the research over the infrastructural aspect is still in its early stage.

From the road infrastructure point of view, there is a large challenge over the success of E-Road structure in its long service lifetime. In other words, integrating the charging facilities into the road pavement can be a complex process, while the follow-up maintenance in the long term run can also be complicated and costly.

Road technologies such as overlay, joint and interlayer systems can enhance the structural integrity of composite road structures potentially. However, their performances are closely related to the practical road structure and also service environment. In this sense, their real effectiveness in E-Road is unknown and needs further investigations.

Long term maintenance management for E-Road is important but also challenged potentially. In this, the use of long term structure health monitoring system and preventive maintenance activities are recommended.

It is just a start point of the research and not all problems are covered in this paper. For instances, the mechanical protection of IPT charging facilities is also important and should be studied; likewise, the suitable road pavement type (rigid, half-rigid, or flexible) and the embedment procedure design is unclear. Nevertheless, this paper showed that more attention should be paid to the practical road infrastructural aspect of the E-Road.

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6 REFERENCES


