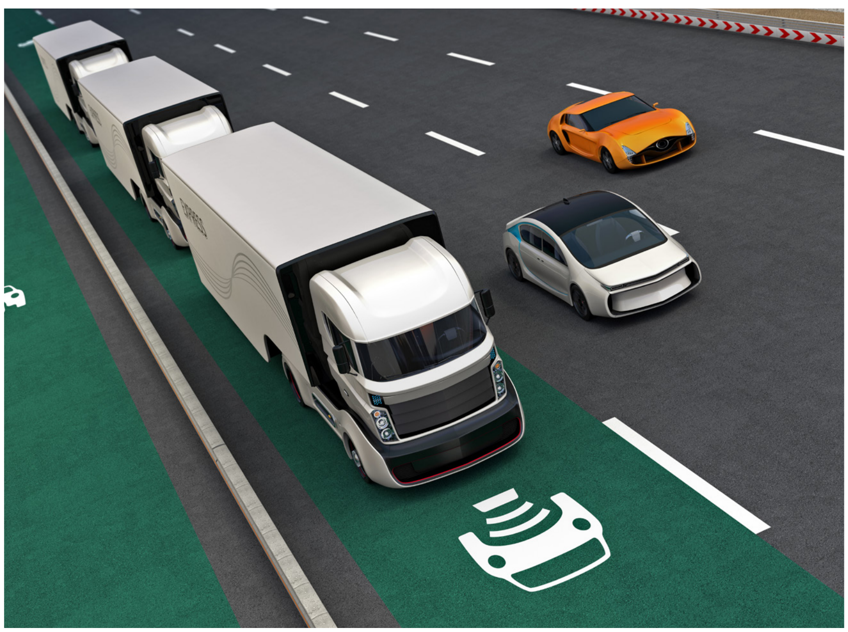
JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY

Feasibility Study and Design of In-Road Electric Vehicle Charging Technologies



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NOTICE

COVER IMAGE

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16. Abstract

Electric Roadways (ERs) or Dynamic Wireless Charging (DWC) lanes offer an alternative dynamic and wireless charging method that has the potential of giving electric vehicles (EV) limitless range while they are moving. Heavy-duty vehicles (HDVs) are expected to be early adopters of the DWC technology due to the higher benefits offered to these vehicles that are traveling on fixed routes. The goal of this project was to assess the feasibility of ERs in Indiana and design a test bed for in-road EV charging technologies. The most suitable locations for implementing DWC lanes were identified on interstates that are characterized by high truck traffic. Using I-65 S as a case study, it was found that DWC can be economically feasible for the developer and competitive for the EV owner at high and medium future projections of EV market penetration levels. However, the existing substations are unlikely to serve future DWC needs for HDVs. Thus, consideration should be given to substation expansion to support EVs as market penetration expands. Implementing the DWC technology on interstates and jointly with major pavement preservation activities is recommended. Large scale deployment can significantly reduce the high initial investment. Renewable energy resources (solar and wind) deployed in the vicinity of ERs can reduce the electricity costs and associated greenhouse gas emissions.

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EXECUTIVE SUMMARY

Introduction

Improving fuel technology and promoting alternative, environmentally friendly modes of transportation, such as electric vehicles (EVs), can be solutions to looming environmental concerns related to the transportation sector. However, EV adoption has been slow, particularly for heavy-duty vehicles (HDVs), due to concerns regarding the range of EVs, lack of infrastructure, and long charging times at charging stations. Dynamic wireless charging (DWC) lanes (also known as electric roadways, ERs) offer a dynamic and wireless charging method that has the potential of giving EVs limitless range while they are moving. For fleet operators and consumers, this could lead to a reduction of battery size, which would reduce the weight and the cost of the vehicle. Furthermore, ERs can improve battery life with reduced discharge cycles and can increase productivity of the vehicle by eliminating long charging times.

HDVs are expected to be early adopters of the DWC technology due to the increases benefits offered to vehicles that are travelling on fixed routes. Indiana has started preparing for the adoption of EVs based on the availability of public charging stations and energy networks, as well as the several state projects that explore "green" transportation technologies. This, combined with the high average daily truck traffic and the need for lower emissions, render the development of new systems to accommodate EV demand a necessity.

In view of the above, the goal of this project was to assess the feasibility of ERs in Indiana and design a test bed for in-road EV charging technologies. The project had the following objectives:

- Conduct a literature review and research best practices.
- Determine selection criteria and identify candidate locations for DWC lanes based on a comprehensive list of demand-related, cost-related, EV-related, and other criteria.
- Design a flexible test bed using modeling and simulation techniques. This objective includes determining the overall architecture of the interconnection with the electric grid and exploring the architecture of the onboard pick-up and charging system.
- Assess the financial feasibility and risk of the technology.
- Offer recommendations to INDOT regarding the implementation of the technology.

Findings

The following constitutes a list of the key findings (and methods) of this study:

- The most suitable locations for DWC lanes are on interstates that are characterized by high truck traffic (especially on I-70, I-65, I-465, I-90, and I-94) as well as near airports and ports, and away from EV charging stations. Distance from intermodal facilities, military bases, planned construction/preservation projects, and floodplains did not significantly affect the identification of the most suitable segments. I-70 and I-65 included more suitable and continuous segments compared to other roads on the network.
- Access to the power network is an important factor in identifying the optimal locations for the technology. A relatively small portion of a candidate highway, I-65 (between Indianapolis and Louisville-I-65 S), could be powered at 100% market penetration. However, the percentage of roadway powered rapidly increases as market penetration decreases. For low penetration levels, roughly 50%–60% of the I-65 S northbound segments could be energized to the level needed to support HDVs. Additional capacity near the corridor would be required to provide full power, but given a slow enough adoption rate, this additional capacity could be installed after construction of the DWC hardware along the road as market penetration increases.
- A DWC power system that is capable of powering HDVs, assuming 100% penetration level and purely electric drivetrains, was designed for a suitable road segment on I-70. Multiple penetration levels of electrified HDVs were considered for the analysis (25%–100%). The results reveal that aggregate power demand may fluctuate significantly, which can be detrimental to power system operations. For 100% penetration, an average load of 16.9 MW (2.2 MW/mi) was predicted. An average power consumption of 4.4 MW (0.6 MW/mi) was obtained for 25% penetration. Significant power ramp rates that can reach as high as ± 15 MW/s were also observed.
- The multi-objective design of the onboard pick-up and charging system of the technology proved its technical feasibility. Adequate power can be transmitted across the relatively large airgap (26 cm/10.24 in) between the transmitter and receiver cores. To overcome the large airgap, the transmitter conductors and core will introduce loss (kW-level) into the pavement. In addition, it is likely that the overall system size (cost) and loss can be significantly reduced if the airgap between the transmitter coil (in the roadway pavement) and receiver coil (on the vehicle) can be reduced.
- Using I-65 S as a case study, it was found that DWC is economically feasible for the developer, and financially competitive for the EV owner at high and medium future projections of EV market penetration levels. The DWC system costs were estimated around \$6.3–6.6 M per lane-mile, assuming a full lane prefabricated construction. If the construction of the ER is scheduled in conjunction with a pavement replacement activity, the respective DWC differential costs range between \$4.6 and 4.8 M per lane-mile. From an operator's perspective, the ER technology for trucks with DWC capability against conventional trucks is competitive at a breakeven point of 30.00 cents/kWh. Payback periods for early adoption deployment of the technology were found to range between 20 and 25 years. Risk analysis unveiled high risks associated with lower projected EV penetration levels, while low risks were associated with a penetration level of 75% for medium and heavy-duty trucks within a 40-year project implementation period.

Implementation

- Implementing the DWC technology jointly with major pavement preservation activities is recommended. Several pavement replacement activities are scheduled for the near future for segments on I-70 that can be potential locations for an ER pilot. While the most suitable locations for the outright commercial operation of this technology are on interstates, a small test bed on a lower-class road project is needed to prove the technology in the field, under real environmental factors and traffic loads.

- Based on the I-65 S case study, the existing substations are unlikely to serve future DWC needs for HDVs. Thus, consideration should be given to the construction of new substations to support EVs as market penetration expands.
- The proposed layout of the power distribution network and the traffic data-driven design methodology for the charging system can be used as a guide to inform future DWC power system designs. The DWC system requires a great amount of power and aggregate power demand may fluctuate significantly. Transmission and distribution systems' available capacity and capability to accommodate the significant power fluctuations are important factors to consider when planning a new implementation of the technology.
- Charging HDVs at levels of 180 kW can be feasibly accomplished using existing transmitter/receiver and power converters—pending validation of the models and the mechanical integrity of the pavements with the embedded transmitter. Model validation and pavement integrity could be readily performed using a small section (12×15 ft) of an ER test bed.
- The use of prefabricated slabs in the ER roadway pavement installation may be used for test beds at the early stages of implementing this technology, since this method allows for trial and error during the slab fabrication process. In the future though, in-situ installation methods may be a better choice to achieve economies of scale. A hybrid method that combines the use of precast panels and in-situ installation methods may also be considered to reduce construction costs.
- The level and growth of penetration of DWC equipped-EVs are among the top contributors to the project's economic success. Regulations and incentives that support the adoption of DWC equipped EVs (similar to ones for conventional EVs), particularly HDVs, would significantly improve this technology's competitiveness and feasibility. DWC system cost also has a great impact on its economics. Large scale deployment can significantly reduce the high initial investment.
- Investments in renewable energy resources (solar and wind) in the vicinity of ERs can reduce the electricity costs and associated greenhouse gas emissions. Renewable energy generation can be complemented with battery energy storage for addressing the intermittent nature of renewable energy generation and reducing impacts on the power grid.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Overview

Advancements in transportation can contribute to major progress in sustainability goals and particularly in energy efficiency. Although the United States (U.S.) has made significant steps towards energy efficiency across its economy, including services and manufacturing, the transportation sector has still room and great potential for improvement. The transportation sector has become less energy efficient over the last 15 years (IEA, 2020) and the largest contributor of U.S. greenhouse gas (GHG) emissions, accounting for 29% of total U.S. GHG (EPA, 2019).

As a result, attempts are made to reduce emissions, including the improvement of vehicle and fuel technology in combination with the promotion of alternative, sustainable modes of transportation. Electrification of transport is among those technological advancements that can decrease levels of emissions, improve fuel efficiency as well as reduce operating costs. However, the share of electric vehicles (EVs) is developing slowly mainly due to raising concerns about driving range, particularly for heavy-duty vehicles (HDVs) that make up for over half of the energy consumption in transportation.

Dynamic Wireless Charging (DWC) lanes (else known as Electric Roadways, ERs) offer an alternative dynamic charging method that holds the potential of giving the EV limitless range while it is moving. For fleet operators and consumers, this could lead to a reduction of battery size, which would lower the weight and the cost of the vehicle. Furthermore, DWC can improve battery life with reduced discharge cycles and no rapid fast charging. This charging solution can also increase productivity of the vehicle by eliminating long charging times.

ERs can be generally developed through two main concepts of dynamic charging: by conductive or inductive energy transfer. In the case of conductive energy transfer, the power transmission can be either based on overhead catenary lines or on rails which are installed in the road (Möller, 2017). The overhead catenary system includes overhead wires which make power available to vehicles and an active pantograph which is located on the top of the vehicle and transfers the power from the contact lines to the vehicle. This way of power transfer is mostly compatible with vehicles of a certain size (HDVs). In the conductive railway system, the vehicle uses a physical pick-up arm to connect to an electrified rail in the road. On the other hand, inductive energy transfer uses a Wireless Power Transfer (WPT) system to dynamically deliver electrical energy to the EV. This is conducted through charging pads or transmitter coils embedded within the roadway that transfer the power to a pick-up unit under the vehicle. This way of power transfer can be practical and beneficial for all vehicle types and thus, it constitutes the focus of this study. Figure 1.1 shows the main components of the DWC technology. This illustration is a concept level drawing of this "smart powered" roadway (ASPIRE, n.d.).

As argued in Chen et al. (2017), commercial fleets, such as trucks, are expected to be early adopters of dynamic charging technology due to higher benefits offered to these vehicles that are travelling on fixed routes. Several transportation infrastructure projects in Indiana involve the cooperation of national utilities and state agencies so as to accelerate the adoption of EVs and explore "green" transportation technologies. This, combined with the high average daily truck traffic and the need for lower emissions, render the development of new systems to accommodate EV demand necessary.

In view of the above, the goal of this project was to assess the feasibility of electric roadways in Indiana and design a test bed for in-road EV charging technologies. The specific objectives or tasks under this main goal are the following:

- *Task 1: Literature Review*
  The first task of this study is to conduct a literature review and gather lessons learned from best practices related to ERs under way. Through the literature review, important information can be obtained regarding the factors that should be taken into consideration for the deployment of the DWC technology in the road network, technology details, methodology used and expected results from demonstrations.

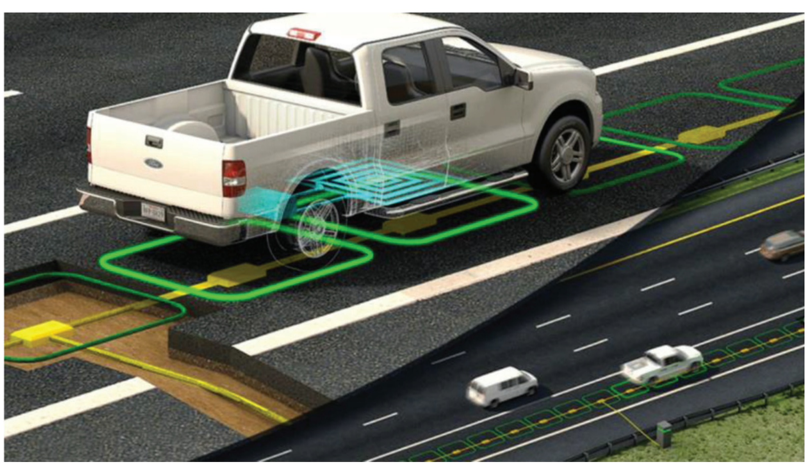

Figure 1.1 Dynamic wireless charging (DWC) technology (Technology Transfer Services, n.d.).

- *Task 2: Selection of Candidate Corridors/Locations*
  This task has the goal to determine selection criteria and identify candidate locations of ERs that can ensure power availability. Based on the literature review, the selection criteria for identifying candidate locations of electric roadways are determined and examined for Indiana's road network. A suitability analysis is then conducted to indicate the most suitable locations for the technology. To ensure power availability, an algorithm is developed that determines which segments of the road can be powered, which substations will be powering these segments, the feeder cable lengths, and the power lost within feeder cables.
- *Task 3: Development and Design of a Test Bed*
  This task is about designing a flexible test bed using modeling and simulation techniques. Outputs from previous tasks are considered such as the synthesis of pilot programs and lessons learned about each technology or the list of locations with adequate access to the power network. More specifically, the task includes the following two closely related subtasks.

  - *Subtask 3.1: Interface with Power Utility and Charging Architecture*
    The objective of this subtask is to determine the overall architecture of the interconnection with the electric utility. This includes all equipment that is downstream from a local substation feeding power to the test bed. This involves a determination of electric system details, such as power, current, and voltage levels, and required equipment (e.g., transformers). This subtask also comprises a detailed design of the terrestrial power electronic stage(s) that act as the interface between the grid and the vehicles, including the design of the in-road charging system (e.g., in-road transmitter technology and design details, spacing, configuration, etc.). Findings are supported by advanced modeling and simulation tools, which are used to quantify the impact of the test bed on the utility grid and to detect/rectify any possible issues in advance.
  - *Subtask 3.2: On-Board Power Electronics and System Design*
    The goal of this subtask is to determine the architecture of the onboard pick-up and charging system(s). This includes details of hardware (e.g., power electronic converters, magnetic/capacitive components, battery storage system, etc.), as well as control system design. Findings are supported by advanced modeling and simulation tools.

- *Task 4: Localized ER Construction Cost Estimation and Financial Analysis*
  Through this task, the financial feasibility and risk are evaluated based on the system architecture in Task 3. This analysis takes into account local considerations including different installation methods and costs. The size/cost of the DWC system are determined utilizing meta-models of the power electronics, passives (inductors/capacitors), the cables/interconnects and packaging. The competitiveness of the DWC technology as an alternative to conventional diesel truck technology was also assessed.
- *Task 5: Recommendations/Guidance*
  Based on the study results, recommendations to Indiana Department of Transportation (INDOT) are offered regarding the implementation of the technology and Phase II of the project that may involve developing a test bed based on the detailed design analysis in Phase I and providing guidance on the construction of a test bed facility.

The proposed framework and models developed in this study for the assessment of the feasibility of DWC can be replicated by transportation planners and other stakeholders and adopted in other locations. Stakeholders can use the findings of this project to successfully design and implement this technology. Multi-criteria decision-making and optimization tools have been proposed to evaluate and identify candidate locations for the technology. Additionally, technical details related to the charging coils and the interconnection to the grid have been provided and can be used as a guide to inform future DWC power system designs. Furthermore, the factors that can contribute to the project's financial success were identified and can be used to form actions necessary to improve this technology's competitiveness and financial feasibility.

1.2 Organization of the Report

The structure of this report is as follows:

Chapter 2 presents an overview of different aspects of ERs and existing work on the technology.

Chapter 3 focuses on the location criteria for the implementation of ERs, the selection of the candidate locations in Indiana and presents a corridor level analysis to investigate the power system availability of a candidate highway.

Chapter 4 describes the architecture of the interconnection of the ER with the electric utility and the architecture of the onboard pick-up and charging system.

Chapter 5 provides information on the financial feasibility and risk of the ER technology and details on the corresponding civil and electrical infrastructure construction costs.

Chapter 6 provides a summary of the key findings, implementation plans, and recommendations as well as opportunities for future research.

2. LITERATURE REVIEW

This section provides a critical synthesis of the literature, regarding different aspects of electric roadways (ERs). The concept of DWC technology is defined, and the main benefits and concerns related to ERs as well as the criteria for optimal locations for implementation of this technology are discussed. Note that since the electric road industry is relatively new, little research has been conducted in this field so far. The characteristics and findings of the existing case studies and research projects in the U.S. and abroad are reported.

2.1 Technology Overview

2.1.1 Dynamic Wireless Charging

2.1.1.1 General Operation. DWC of EVs is based on the concept of transferring power between two coils, a transmitter coil and a receiver without any wired connection between them. The transmitter coil is embedded within the roadway pavement, and the receiver coil is placed on the vehicle. Power is transferred via the electromagnetic field that is developed in the air gap between the transmitter and receiver for the purpose of charging the vehicle's battery.

High-frequency current is passed through the transmitter coil to generate a time-varying magnetic field as per Ampere's law. Through this magnetic field, the receiver coil is linked with the transmitter and, according to Faraday's law, voltage is induced on the receiver coil. To generate a high-frequency current, an inverter is used on the transmitting side, and a rectifier is used on the receiving side to feed DC voltage to the vehicle's battery (Bateman et al., 2018).

In practical DWC systems, a resonant magnetic induction method is used as it currently provides the highest efficiency of power transfer (CORDIS, 2017). The resonant circuit includes so-called compensating inductors and capacitors that are used to negate the effect of the relatively large leakage field of the transmitter.

2.1.1.2 Market Overview. In recent year, stationary charging of EVs has become commercially available. Advances in the charging technology have made it feasible for multiple companies to develop and provide this type of product to the market. Some of the primary companies with commercial stationary wireless charging solutions are WiTricity, Qualcomm, Conductix-Wampfler, Momentum Dynamics, and HEVO power.

WiTricity, which is a spin-off from the Massachusetts Institute of Technology, provides charging rates for static inductive wireless charging from 3.6 to 11 kW. The highest efficiency reported is 94% from grid to battery. They use a circular coil architecture and are capable to adopting to the clearance of an SUV (25 cm). Tolerance to parking misalignment of +/-10 cm side to side and +/- 7.5 cm front to back. The charging pad can be installed on-ground or buried in pavement (WiTricity, n.d.). WiTricity have also recently acquired Qualcomm's EV wireless charging unit Halo (WiTricity, 2019). Halo was tested for dynamic charging in Versailles, France through the FABRIC project (CORDIS, 2017). Conductix-Wampfler offers contactless charging solutions for industrial applications such as transfer cars, skillet lines with lift tables, Automated Guided Vehicles (AGV) or Rail Guided Vehicles (RGV). Their solutions operate at 20 kHz (Conductix-Wampfler USA, n.d.). Momentum Dynamics developed high power inductive charging technologies for the automotive and transportation industries that can deliver energy safely through air, water, and ice (all weather conditions). They offer up to 75 kW chargers for EVs and up to 200 kW charging systems for mass transit (https://www.momentumdynamics.com/). HEVO power also offers a 10-kW static charger.

DWC is presently not commercially available due to multiple challenges in infrastructure modification and the requirement of highly efficient power transfer (Patil et al., 2017).

2.1.1.3 Technology Standards. SAE International published SAE J2954 Recommended Practice (RP) for Wireless Power Transfer for Light-Duty Plug-in/EVs and Alignment Methodology in May 2016, and its latest revision was published in April 2019 (SAE International, 2019). The RP defines acceptable criteria for interoperability, electromagnetic compatibility, EMF, minimum performance, safety, and testing for wireless charging of light-duty electric and plug-in EVs. Four levels of charging according to power levels are categorized up to 22 kW. It supports home (private) charging and public wireless charging. A standardized single coil test is developed for power classes 1, 2, and 3, up to 11 kW (1 through 3) using circular topology but also provides a way to demonstrate compatibility to other coil topologies.

The J2594 specifies target efficiencies of the system at all power levels with a minimum of 80% for offset positions as shown in Table 2.1. Table 2.2 summarizes the J2594 standard requirements for ground clearance. Power transfer with a side-to-side tolerance of +/-100 mm (+/-4 inches) is also required as shown in Table 2.3. The alignment criteria assist the driver to stay within the charging range even when it is difficult to park with precision.

EV wireless charging involves several disciplines and for this reason, there are many international organizations working on standards and guidelines. Examples of these organizations are IEC, ISO, ICNIRP, CISPR11, ITU, ETSI, SAE, IEEE and national bodies. Related standards cover the topics of power transfer equipment, communication between the power grid, vehicle and charging infrastructure, interoperability and health and

TABLE 2.1
WPT power classifications for light-duty vehicles

	WPT Power Class			
	WPT1	WPT2	WPT3	WPT4
Maximum input VA	3.7 kVA	7.7 kVA	11.1 kVA	22 kVA
Minimum target efficiency at nominal x, y alignment	>85%	>85%	>85%	TBD in next phase
Minimum target efficiency at offset position	>80%	>80%	>80%	TBD in next phase

TABLE 2.2
Specification of the Z-classes

Z-Classes	VA Coil Ground Clearance Range
Z1	100 to 150
Z2	140 to 210
Z3	170 to 250

TABLE 2.3
Positioning tolerance requirements for tests station vas and product vas

Offset Direction	Value (mm)
⊿X	±75
⊿Y	±100
⊿Z	–

safety. The topic of power transfer equipment covers connection to the grid, EMC (electromagnetic compatibility), harmonics and safety standards (CORDIS, 2017).

2.1.1.4 Technology Characteristics

Basic System Architecture for EV Charging. The overall WPT architecture for EVs is shown in Figure 2.1. The high-frequency power supply at the sending end consists of an ac-dc converter to convert the ac utility power into dc, and a dc-ac converter that converts the dc current and voltage into high-frequency ac. Modern switching elements and converter topologies are used for these purposes. The high-frequency ac current passes into the compensation tank which consists of passive elements, capacitors, and inductors. The capacitors and inductors are arranged such that they resonate at a frequency that is matched with the receiver side.

A high-frequency ac signal is received at the receiving side and passes through the compensation tank that is tuned to the same frequency as the sending-end tank. The second stage is a rectifier that transfers the current and voltage signals back to dc to charge the EV battery.

Coils. DWC requires the receiver coil to be in alignment with the transmitter coil in order for coupling to occur between the coils and power transfer to take place. The coupling coefficient between the two coils is a fundamental parameter in determining the power transfer efficiency and power transfer capability of the DWC system (Covic & Boys, 2013).

The design of the coupled coils has an immense impact on system efficiency, and their design is therefore a critical aspect. Coils used in this technology are categorized as either unipolar or polarized. Unipolar coils have one magnetic pole per coil face. Magnetic flux leaves the coil face of the transmitter (north pole) and enters the receiving coil (south pole). To achieve this type of coupling, simple coils with either circular or rectangular structures are used. A bipolar coil obtains both north and south poles at each coil face. Flux lines leave the region of the coil face with the north pole and enter a region with the south pole on the same coil face. For this reason, flux is restricted within the space between the coils which increases the coupling coefficient, increases tolerance to vehicle misalignment and reduces leakage flux (Choi et al., 2014). Tripolar coupling coils also appear in the literature, with an even more complex structure and control (Patil et al., 2017).

Transmitters are usually made of a combination of Litz wire for the conductor, ferromagnetic material to supply a path for magnetic flux, and aluminum for electromagnetic shielding in locations that the electromagnetic field is undesired. Litz wire is generally used for the coil conductors due to its relatively low resistance expected at the frequencies of modern transmitters/receivers. Ferromagnetic material is commonly used to improve the coupling coefficient and to control the shape of the magnetic flux path. Aluminum is also used for the purpose of fully containing the magnetic flux underneath the vehicle even when there is misalignment between the transmitter and receiver (Lukic & Pantic, 2013).

Charging Power Track for Dynamic Wireless Charging. The charging of EVs while in motion is referred to as Dynamic Wireless Charging. To charge, EVs equipped with a compatible receiver coils must drive over an electrified roadway, which is a road section that contains transmitter coils. To electrify a roadway, transmitters are created in short, segmented segments, or as a single long segment (Patil et al., 2017).

Segmented transmitters have a string of short transmitter coils, each of which are embedded within the road structure at specified distances between coils. Each coil in this set-up uses a power supply to convert between a DC input and the AC transmitter output. The coils are only energized when a receiver equipped EV passes on top of each coil. A segmented setup has the advantage of compact structure which simplifies the construction process. However, the potential

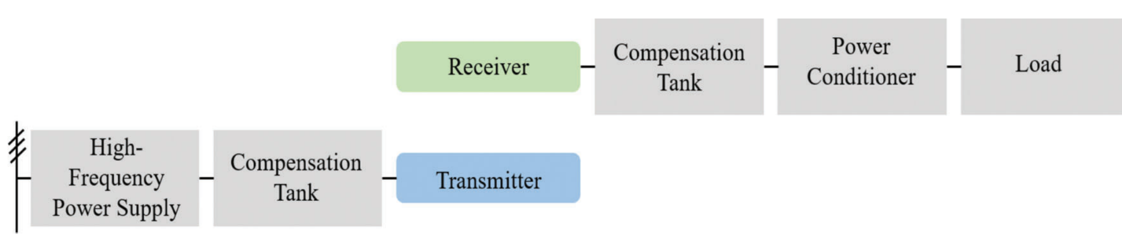

Figure 2.1 Typical wireless charging system for EVs.

disadvantages of this set-up arise in the complexity arising from the multiple connections that need to be made to energize all segments, as well as a reduction in reliability due to the number of power converters and transmitter/receiver components in the system. An alternative to the segmented design is to use a single long transmitter section embedded within the roadway. In such a case, the transmitter is energized full time regardless of the presence of an EV. This set-up requires a simple power supply structure and control. On the other hand, energizing the coil continuously results in a continuous loss of energy. Thus, to reduce the waste of energy and leakage flux, the segmented transmitter is considered herein (Choi et al., 2014).

Compensation Network and Power Electronics. The transmitter and receiver coils can be characterized as coupled circuits that resemble a transformer. In contrast to transformers utilized in utility power systems, the transmitter/receiver coils are separated by a large airgap between the road and underside of the vehicle. As a result, they have a relatively low magnetizing inductance, and relatively high leakage inductance. As a result, a significant ratio of reactive to real power is required from the input power source, which means it requires a relatively high apparent power rating (VA in order to transfer active power to the vehicle). To overcome the large leakage reactance and maximize power transfer, compensation circuits are placed between the dc-ac converter and transmitter coil and between the receiver coil and onboard ac-dc converter. The compensation circuits consist of series-parallel combinations of capacitors and inductors.

Power supply architecture depends on the charging power track design. In the long transmitter rail design, a single power source drives the entire rail to maintain constant current. This centralized design requires the electronic components to be rated for relatively high-power levels. Additionally, the power track is energized all the time which incurs large power losses and reduces reliability.

The segmented transmitter can be supplied with power in multiple ways. An H-bridge inverter can be connected to each transmitter. Another approach is to supply multiple transmitters with a single high-power inverter, and each transmitter is turned ON or OFF individually via a switch. In both cases, the segmented approach allows each transmitter to be turned on or off based on the motion of equipped EVs aligned with it. Power loss in this case is lower and reliability is improved. Disadvantages of this configuration are its higher cost, higher maintenance requirements and more complex control of the power supply (Patil et al., 2017).

2.1.2 Ferrite Core Geometries

Ferrous material is used in the transmitter and receivers to reduce the magnetic reluctance between transmitter/receiver cores. Some of the ferrous-material-based transmitter geometries found in literature are explained below.

2.1.2.1 E-type Core. The E-type core consists of an E shaped transmitter ferrite core which looks like an E laid on its back such that the three legs point in the vertical direction. The transmitter winding is laid along the length of the transmitter on one side of the middle leg and returns from the other side making a loop around the middle leg. The receiver is also shaped like an "E" but has broader faces in order to collect the magnetic flux generated by the transmitter. The geometry of the E-type core is shown in Figure 2.2.

An advantage of the E-type core is that it is capable of handling more magnetic flux without saturating the core. This is due to the two limbs on either side of the E core which need to carry only half the magnetic flux generated by the middle limb. The primary disadvantage of the E-type core is that it is more sensitive to lateral displacement of the receiver (Shin et al., 2014).

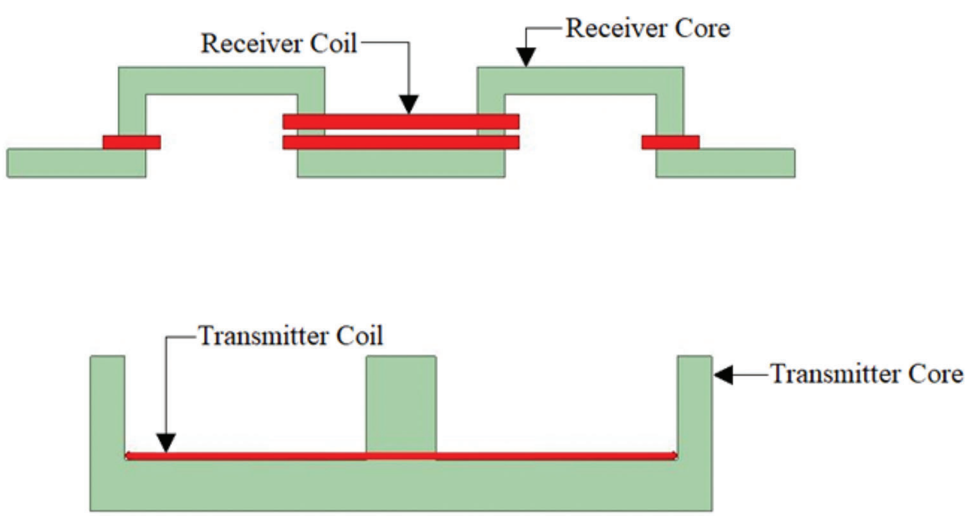

Figure 2.2 E-type core.

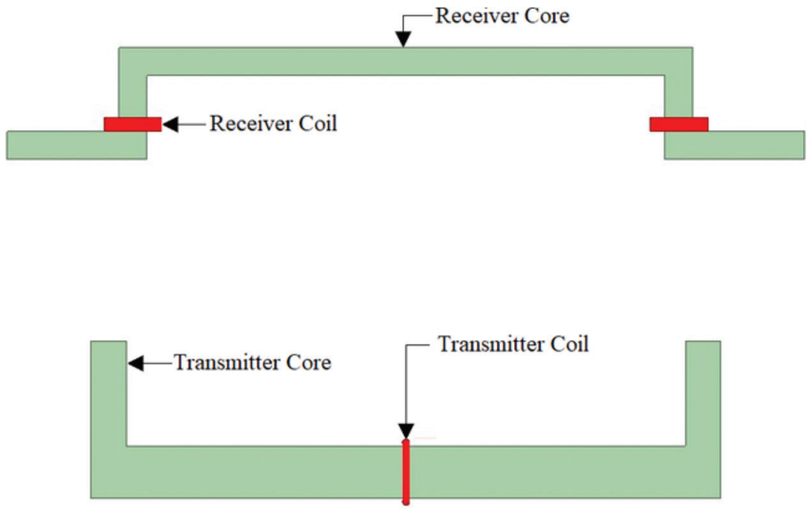

Figure 2.3 U-type core.

2.1.2.2 U-type Core. The U-type core is similar to an E-type core except that the ferrite core is now shaped in the form of a "U." The transmitter winding/coil is wound around the back or any one or both of the limbs of the core. The receiver is shaped like the transmitter except with broad faces to facilitate flux collection. Figure 2.3 shows the geometry of the U-type core.

The main advantage of the U-type core is that it is more tolerant to lateral displacement of the receiver compared to its E type counterpart. But unlike the E-type core the U-type core is more susceptible to saturation which can decrease the power transfer capability (Shin et al., 2014).

2.2 Case Studies

Different studies across the world focus on exploring dynamic charging. Table 2.4 shows the main information about the research projects and case studies that exist on the dynamic wireless charging in the U.S. and abroad.

2.3 Economic Analysis/Viability Studies

There have been several research studies on the economic viability of dynamic charging. Table 2.5 presents a list of research studies that focused on the economic viability, initial investment cost, and/or operations cost of this technology. The cost of the supporting infrastructure has also been reported as part of different demonstration projects. Table 2.6 provides estimates of the infrastructure cost by each project and organization, as reported by Bateman et al. (2018). It is noted that the data, assumptions and methods used across the various studies or projects are different. Therefore, the findings and conclusions reported in the studies cannot be treated as conclusive or representative.

2.4 Optimal Locations

The identification of the optimal locations of the dynamic wireless charging technology can be crucial to the success of the system and thus, certain factors should be considered to ensure that the location selected is suitable. According to the literature, common factors are the following.

2.4.1 Demand-Related Criteria

A primary factor for locating the technology is the daily traffic of the candidate roads (Stamati & Bauer, 2013). According to Limb et al. (2016), the technology should be deployed in areas with high traffic. Since trucks are expected to be among the first adopters of the technology (Chen et al., 2017), it would be reasonable to examine roadway segments that are key trucking corridors. This criterion is generally important for emerging technologies and has been extensively used in different suitability analyses for truck-only lanes, freeway corridors for managed lane strategies, etc. (e.g., Reich et al., 2005). Proximity to land designated for specific uses, such as airports, ports, intermodal facilities, and military bases, also plays a major role in determining the optimal locations for ERs, according to the patterns found in ER-related case studies. Such locations are the origins and/or destinations of a high percentage of heavy/light-duty vehicles and can simultaneously contribute to the public recognition of the technology (Siemens AG, 2017).

2.4.2 Cost-Related Criteria

It has been reported that the largest part of the cost of ERs comes from the construction and installation work itself, being around one-third of the total implementation costs of the technology (e.g., Jelica, 2017). In this context, it may be important to link the

TABLE 2.4
Dynamic wireless charging research projects and case studies

Reference	Location	Test Track/Site	Vehicle Type	Results/Goals
Eghtesadi, 1990 Systems Control Technology, Inc., 1994 Vilathgamuwa & Sampath, 2015	Berkeley, CA, U.S.	0.13 miles stretch, Berkeley	Battery-electric bus	Measured: Operating frequency of 400 Hz; 0.26 ft air gap 60% efficiency rate
Utah State University, 2012 Limb et al., 2016 Tavakoli et al., 2016 Möller, 2017 Suul & Guidi, 2018	Logan, Utah State, U.S.	Quarter mile test track Shuttle service to Utah State University Community,	20-passenger “Aggie” electric bus	Goals: 25–50 kW power transfer of transmitter; 1.15 ft 90% efficiency 20% reduction in air pollution 10% reduction in CO_2 emissions $180 B in annual cost savings
Highways England, 2015 De Blas, 2017 Möller, 2017	Versailles, France, EU Turin, Italy, EU	0.062 miles test track, Vedecom/ Qualcomm solution 0.43 miles test track, SAET and POLITO solutions	Electric cars and vans	Measured: 20–100 kW charging power; 0.66 ft air gap 80% efficiency
Brecher & Arthur, 2014 Highways England, 2015 IPT Technology, n.d. Sundelin et al., 2016 Möller, 2017 Suul & Guidi, 2018	Berlin, Germany, EU Braunschweig, Germany, EU Lommel, Belgium, EU Mannheim, Germany, EU Sdertlje, Sweden, EU	3.79 miles route 7.46 miles route 0.75 miles route 5.59 miles route 6.21 miles route	Hybrid electric truck	Measured: 40–200 kW charging power; 0.33 ft air gap 89% efficiency
INTIS, 2016 Suul & Guidi, 2018	Lathen, Germany, EU	0.016 miles test track	Electric passenger and commercial light vehicles (car, bus, minivan)	Measured: 30–50 kW power transfer (coil system); 0.33 ft air gap
Bludszuweit, 2016 Rim & Mi, 2017 Ahmad et al., 2018 Jang, 2018 Suul & Guidi, 2018	Malaga, Spain, EU	0.062 miles stretch with low speeds (6.2 mph)	Battery electric bus	Measured: 50 kW power transfer; 0.5 ft–0.66 ft air gap 83% efficiency
Lee et al., 2010 Suh et al., 2011 Ko & Jang, 2013 FABRIC, 2014a Shin et al., 2014 Jang et al., 2016 Suh & Cho, 2017	Gumi/Seoul/Daejeon, South Korea, Asia	Transit buses Tram at Seoul Park Amusement Park Shuttle system of KAIST campus	Battery electric bus (OLEV buses) Tram/rail	Started from 2009 Already in use Measured: 60–200 kW charging power; 0.56 ft–0.85 ft air gap; 75%–85% efficiency rate
Electreon, 2017	Tel Aviv, Israel, Middle East	65 ft test track, Tel Aviv	Battery electric bus	0.79 ft; More than 88% efficiency
Highways England, 2015	United Kingdom, EU	Not field trials yet	Electric cars, large, good vehicles, heavy, good vehicles	Investigation of different WPT systems, expectations mention up to 100–140 kW of power transfer More than 80% efficiency

TABLE 2.5
Summary of economic analysis/viability studies

Reference	Focus of Study	Location/Vehicle Type	General Description	Key Results
Bansal, 2015	Operations cost	–	Comparing plug-in and dynamic wireless charging	The cost of charging per mile is less in the case of a DWC system on a highway or a traffic signal ($0.19/mile) than the case of the plug-in system at charging stations ($0.42/mile).
Fuller, 2016	Initial investment, operations cost	California/passenger EV	Comparing conventional gasoline refueling	Travel with a 200-mile EV and a 40 kW DWC lane can be achieved at a cost of $4 M/lane-mile. Dynamic charging, combined with static charging, is more cost effective than gasoline refueling over a 10-year period.
Jang et al., 2016	Initial investment cost	OLEV at KAIST and Gumi/transit bus	Comparing stationary, quasi-dynamic, and dynamic wireless	DWC is less cost efficient for a short trip service. It can be competitive with the stationary or quasi-dynamic options if a bus operates a minimum travel distance. The OLEV-based transit system at Gumi City needs to have at least 18 buses in operation to be economically competitive.
Jeong et al., 2015	Initial investment cost	OLEV at Gumi/transit bus	Considering battery lifetime in optimization model/Including battery cost	The optimal cost of DWC (installation and battery cost) was approximately $11 M in total for stationary charging transit buses, which could be reduced to $9 M if replaced with dynamic charging (total power track installation cost is around $660 K to install seven power tracks 0.38 miles long).
Ko & Jang, 2013	Initial investment cost	OLEV at Seoul Grand Park/transit bus	Using OLEV cost figures and optimization techniques	The minimum cost of installing an OLEV-based system is about $640 K including charging infrastructure and cost of batteries; excluding the bus units, construction, and labor.
Limb et al., 2019	Economic viability	US/light-duty vehicles and Class 8 trucks	Comparing internal combustion engine (ICE) with WPT EV. Payback is achieved by a reduction in cost from fuel delivery and availability	The national return on investment is 32 years with $98 B per year. The summed costs for the WPT vehicles decrease by 44.8% for light-duty vehicles and by 63.2% for Class 8 trucks, compared to conventional ICE vehicles.
Park & Jeong, 2017	Initial investment cost/operation cost	OLEV at Gumi City/transit bus	Reporting the operational cost and investment cost of OLEV at Gumi City and comparing to those of compressed natural gas (CNG) based bus	The construction and installation of wireless charging infrastructure would cost $726 M if an installation cost of $0.8 M/mile on the 6% of the total traffic lanes in Seoul can be assumed. The costs of operating OLEV and CNG buses are $14,136 and $52,932 per year, respectively.
Shekhar et al., 2016	Initial investment cost	Electric bus fleet	Development of a generalized economic study of employing a wireless on-road charging system for driving range extension	The cost is estimated to be around $2 M/lane-mile for a lifetime of 12 years and for with a charging power level of 200 kW.
Sheng et al., 2020	Economic viability	Auckland, New Zealand/EVs	Using a net present value (NPV) framework, to identify the optimal public-private partnership (PPP) ratio	The government can contribute 9.46% towards the initial investment for DWC and charging roadway users a toll of 37 cents/kWh, for a 15-year concession period under PPP where the private investor is expecting a 12.5% return.
Sproul et al., 2018	Economic viability	US/Class 8 trucks	Comparing ICE with WPT EV and a long-range battery electric truck	WPT truck has an estimated overall cost that is 35% lower than an ICE truck and 21% lower than a long-range battery truck.

TABLE 2.6
Infrastructure cost estimates from DWC demonstration projects

Project Name	Organization	Vehicle Type	Estimation of Infrastructure Cost ($/lane-mile)
OLEV	KAIST (South Korea)	Buses, light-duty vehicles, tram/rail, passenger vehicles	900 K
ORNL WPT	University of California, Berkeley (U.S.)	Light/heavy-duty vehicles, passenger vehicles	1.9 M
ORNL WPT	Oak Ridge National Laboratories/OEM's (U.S.)	Passenger vehicles	2.4 M
PRIMOVE	Bombardier/Scania (Germany/Sweden)	Buses, heavy-duty vehicles, passenger vehicles	5.7 M–10.8 M (3.1 M final expectation)

installation of ER technology with the implementation of any planned maintenance/resurfacing/reconstruction activities to reduce the cost of deployment and minimize the disruption to the road networks during ER construction (Bateman et al., 2018; FABRIC, 2014b). According to experts' opinions from the state transportation department, the "heavier" roadway pavement work types, such as a total pavement replacement or new road construction, may be more appropriate than "lighter" work types, such as pavement overlays, to be combined with ER deployment.

Once implemented, ER technology will draw a significant amount of electric power, and the goal of an ER deployment strategy would be to distribute the technology in such a way that sufficient power is available. As a result, access to the power network is an important factor in identifying the optimal locations of the technology. In Los Angeles, a feasibility analysis of ERs was conducted that involved researching the distance of candidate road segments from substations (Siemens AG, 2017). The analysis found that the distance of ERs from substations should be less than 1 mile to ensure sufficient energy distribution; however, this distance may differ depending on the density of substations in each candidate area. The expected loading/capacity from the substations should also be estimated since it will determine the power capability of the system and determine the suitability of each substation for connection to an ER.

2.4.3 EV-Related Criteria

The locations of existing EV charging stations can influence decisions regarding the placement of ERs. While a common approach to locating ERs might be to consider existing charging stations as candidate locations because the infrastructure is in place and the demand patterns are known (e.g., Turchetta et al., 2018), the opposite may actually apply in the case of ERs. In particular, it is sensible to assume that locating ERs away from existing charging stations can allow for longer trips and help avoid multiple "re-energizing" stops. This way, ERs can also cover any service gaps between existing EV charging stations. Market penetration of EVs is also an essential aspect to locating ERs. More specifically, it is recommended that ERs be built in areas with the highest penetration of EVs (Stamati & Bauer, 2013).

2.4.4 Supply-Related Criteria

The identification of suitable locations for ERs also depends on the road characteristics and road environment of candidate locations. It is recommended that ERs be positioned in a way that limits the physical constraints that the road environment imposes on the system. As a result, the availability of space on and within the road (for the wireless inductive system) and the terrain features are critical factors in ER placement. Another aspect of road characteristics is related to the proposed length of the ER (Stamati & Bauer, 2013). While it seems technically feasible to make longer segments and thereby, design an ultimately less expensive system, longer segments can reduce the practical availability of power transferred to vehicles. Shorter segments might instead be chosen because they have the advantage of enabling the transfer of power to slow moving or stopped vehicles (Olsson, 2013). In either case, based on the initial goals and assumptions for the length of the ER infrastructure, it should be ensured that the existing candidate road is long enough to implement the technology. The length of the proposed segment is also associated with the accessibility to and capabilities of the local power network.

2.4.5 Other Criteria

Locations that commonly experience problems related to water accumulation or flooding should be avoided, since there may be a risk of frost damage to the ER (Olsson, 2013). Moreover, ERs are expected to reduce emission levels in the long run based on several studies (e.g., de Blas, 2017; Limb et al., 2016). Therefore, areas with high levels of emissions can be identified and considered as candidate locations in order to alleviate their environmental problem in the long run.

2.5 Benefits and Concerns/Challenges

There are certain benefits and concerns associated with the implementation of the dynamic wireless charging technology (Bateman et al., 2018; Highways

TABLE 2.7
DWC-related benefits of and concerns

Benefits	Concerns
It is safer in terms of road user or worker interaction.	There will be more power losses compared to the conductive systems.
It does not impose on established winter maintenance activities.	It is not easily accessible and thus, maintenance may be more strenuous.
There is no visual pollution since the system is embedded in the road.	It requires roadside equipment installations at frequent intervals.
It is suitable for all types of vehicles.	It can have increased cost since it does not only involve the addition of the electrical components but also the alteration of the existing pavement to accept its components.
It is less vulnerable to damage or vandalism.	
It is a technology that is widely applied in the charging of EVs.	

England, 2015). The main advantages and disadvantages of this type of technology are summarized in Table 2.7.

3. SELECTION OF CANDIDATE LOCATIONS FOR IN-ROAD ELECTRIC VEHICLE CHARGING

To effectively implement the ER technology in Indiana, charging lanes need to be strategically deployed in the road network. Based on Chen et al. (2017), HDVs, such as trucks will be among the first adopters of this technology. Furthermore, Indiana has been characterized as the crossroads for the nation's transportation systems (Cambridge Systematics, Inc., 2018) and it is among the leaders in truck tons originated and received through its 14 trucking interstates (Conexus Indiana Logistics Council, 2017). For these reasons, the deployment of a wireless dynamic charging system on the road freight transportation network of Indiana would be worth exploring. In this chapter, the state level analysis conducted to indicate the most suitable locations for the technology and the corridor level analysis to investigate the power system availability of a candidate highway are described in the next sections.

3.1 State Level Analysis

Portions of this section are published in: Konstantinou, T., & Gkritza, K. (2021). A multi-criteria decision-making approach for a statewide deployment of dynamic wireless charging for electric vehicles. *Advancement in Transportation Studies*, (53), 5–22.

Many factors need to be considered in the process of identification of candidate electrified corridors statewide and thus, the analysis is based on multi-criteria decision-making. Among the criteria found in literature, nine criteria were used in the analysis that are divided into four groups: (1) demand related (truck traffic, proximity to airports, intermodal facilities, military bases and ports), (2) cost related (existence of construction projects and preservation projects), (3) EV related (distance from existent EV charging stations) and (4) other criteria (floodplains).

Since a state-level spatial analysis that can consider multiple criteria for the optimal deployment of ERs has not yet been implemented, a Geographic Information System (GIS)-based multi-criteria suitability analysis was conducted. The objectives of the analysis were the following:

- Create a GIS and link-based screening (spatial) model to identify suitable locations for ERs.
- Conduct a sensitivity analysis to assess the relative importance of the criteria considered in the analysis.
- Evaluate the results for the potential ER deployment to ensure feasibility of implementation and propose specific locations in the road network.

The information obtained from this study, including the location criteria for the technology and the methodology used, can facilitate the decision-making process, and be used by INDOT to design and deploy the technology effectively and efficiently.

3.1.1 Data and Methods

The following table (Table 3.1) shows the data needs and sources for each criterion considered in the analysis. The data obtained were in the form of GIS layers. Figures A.1–A.4 in the Appendix show the layers of the related data.

The ArcGIS ESRI software (version 10.1) was used for this analysis. The methodology followed is summarized in Figure 3.1, including the necessary inputs and the output of the analysis.

In particular, the data layers were compiled in GIS and for the layers that correspond to criteria that involve a distance calculation, buffers were created reflecting the Euclidean distance from each facility. The layers were rasterized (700-meter grid) and reclassified using a 5-point scale, with 1 reflecting the most suitable value for a location and 5 the least suitable value. Table A.1 in the Appendix shows more details on the classification values used for the raster layers. After reclassification, the determination of the weights was the next step. Equal weights were considered for the main part of the analysis (base case) for all the location criteria. The criteria weights and the standardized criteria maps (or raster layers) were combined by means of the weighted sum method (additive weighted overlay). In this approach, it is assumed that the more favorable the factors, the more desirable the candidate location will be. A total score is obtained for each road segment by multiplying the weight assigned for each criterion by the scaled value given to the location on that criterion

TABLE 3.1
Criteria and data used in the suitability analysis

Type	Rationale	Data	Data Sources (date)
Demand-related	The deployment of ERs should be on the main road network of Indiana and should cover the maximum amount of truck traffic ("Truck traffic")	Traffic network and annual average daily truck traffic per road segment (traffic message channel [TMC] segments as defined by INDOT)	INDOT Asset Management, Program Engineering and Road Inventory
	The deployment of ERs should be in proximity to primary airports ("Airports")	Locations of airports (primary)	Indiana Map (2005)
	The deployment of ERs should be in proximity to intermodal facilities ("Intermodal facilities")	Locations of intermodal facilities	Bureau of Transportation Statistics, National Transportation Atlas Database (1997)
	The deployment of ERs should be in proximity to military bases ("Military bases")	Locations of military bases	Military Mortgage Center (2019)
	The deployment of ERs should be in proximity to ports ("Ports")	Locations of ports	Bureau of Transportation Statistics (2021)
Cost-related	The deployment of ERs should be combined with planned roadway pavement preservation and construction projects (*this counts as two separate criteria: preservation and construction projects)* ("Construction/ preservation projects")	Locations and characteristics of planned construction/maintenance activities. The specific work types included in the analysis (based on experts' opinions) are divided into added capacity (addition of travel lanes, new road construction) and reservation/ maintenance (pavement replacement, road construction/rehabilitation, patching and rehab of PCC pavement)	INDOT's Next Level Roads Program (2019)
EV-related	The deployment of ERs should be at a distance from EV charging stations ("EV charging stations")	Locations and types of EV charging stations	Alternative Fuels Data Center (2019)
Other (environmental)	Areas with high chances of flooding should be avoided ("Floodplains")	Floodplains	Indiana Department of Natural Resources (2019)

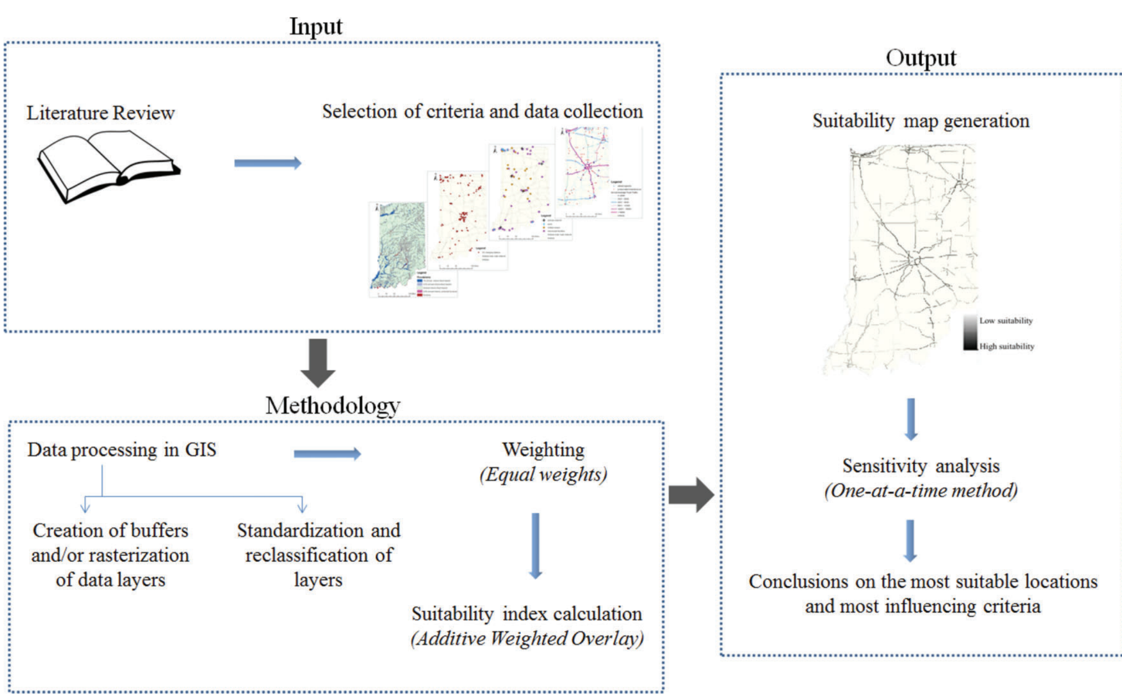

Figure 3.1 Methodological framework.

and summing the products over all criteria. The zonal statistics tool was used for this purpose.

A sensitivity analysis was also conducted to examine the influence of the weights of criteria in the results of the suitability of the segments. The input weight of each criterion was changed one-at-a-time (OAT method) (Daniel, 1973). The main advantage of this method is that any change observed will undoubtedly be due to the single factor changed, increasing the comparability of the results. For each criterion, three weighting schemes were examined (0.3, 0.5 and 0.7) and for each scheme all the other criteria were given equal weights in such a way as to add up to one. The analysis run for 27 times (9 criteria times 3 weighting schemes). The corresponding suitability maps were generated, and the road segments were classified in the same way as the suitability map of the base case.

3.1.2 Findings

Figure 3.2 presents the results of the suitability analysis. In particular, five classes of suitability for ERs were created and labeled as shown in Figure 3.2 for each road segment. The ranges of the suitability indices per class are shown in the figure's legend (Figure 3.2).

According to the results, the segments with the highest suitability were found to cover 1,820.17 roadway miles or 19.89% of the total miles of the road network. These miles correspond to 1,677 most suitable segments or 30.60% of the total road segments, as defined by INDOT. The corresponding percentages for the rest of the suitability classes are the following: for the "high" suitability class 13.29% of the total miles and 16.33% of total road segments; for the "medium" suitability class 7.67% of the total miles and 3.96% of total road segments; for the "low" suitability class 24.37% of the total miles and 19.98% of total road segments; for the "lowest" suitability class 34.78% of the total miles and 29.14% of total road segments. By observing the results, the "zones" identified to include the most suitable segments are the following: segments around Indianapolis and in the northwestern part of Indiana (near Lake Michigan).

It was generally noticed that the majority of the most suitable segments are located on interstates and especially on I-70, I-65, I-465, I-90 and I-94. This may

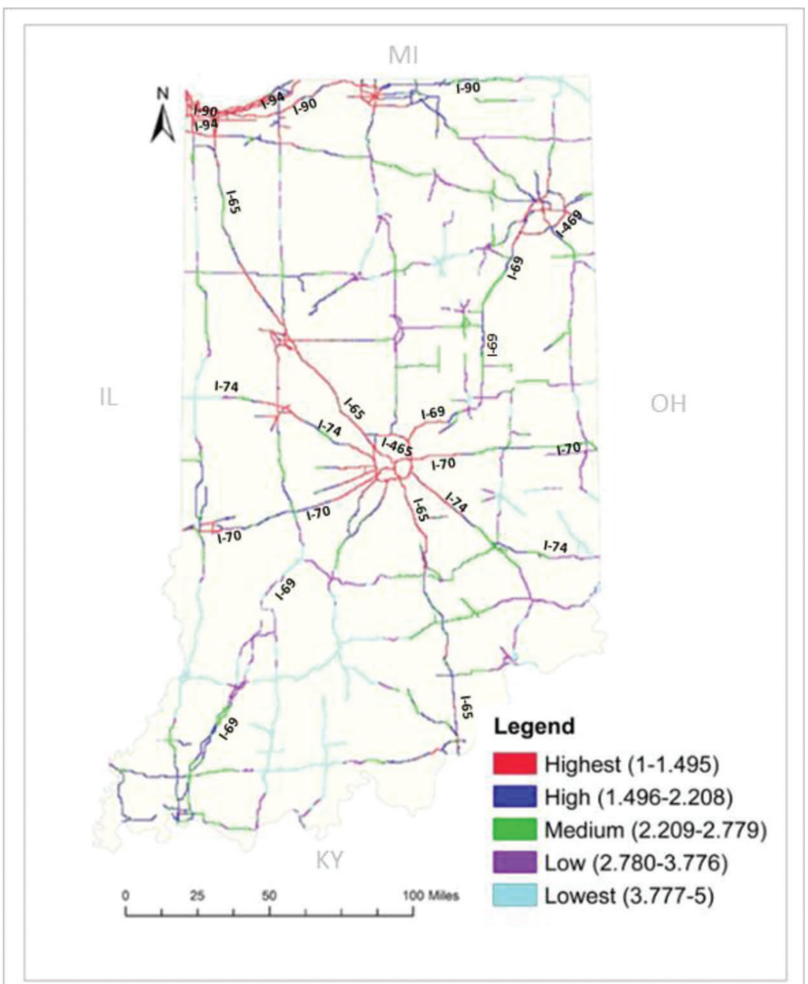

Figure 3.2 Suitability analysis results assuming equal weights of criteria.

be reasonable since truck traffic and different facilities and infrastructure are concentrated on/near interstates. This also has an interesting implication in that the interstates of Indiana will be part of the Alternative Fuel Corridor Program, which seeks to establish a national network of alternative charging infrastructure along national highway system corridors (FHWA, 2021). Note that the suitable locations on interstates are mostly recommended for the commercial operation of this technology. Initial test beds may also be located on non-interstates to allow for experiments before the technology's full commercial operation.

It is important to mention that the suitability map displays certain stretches of interstate where multiple consecutive segments were found to be most suitable. This means that the majority of the most suitable segments were found to be continuous or next to each other on specific interstates, indicating the potential for the construction of a system with longer ER corridors, not only potential shorter charging lanes that may have the length of a single road segment. Most scenarios indicated the I-70 and I-65 may include more continuous segments compared to other roads of the network. In an attempt to find a combined suitability for each of these interstates, they were divided into two continuous stretches. For I-70, the stretches are located west and east of Indianapolis and for I-65, the stretches are located north and south of Indianapolis. For those stretches, a weighted average suitability index was calculated based on the miles of the segments that belong to each stretch of highway. The index for each stretch was calculated by summing the product of the suitability index of each road segment by its length and then dividing by the total length of the stretch. The results are shown in Table 3.2.

TABLE 3.2
Weighted average suitability indices for I-70 and I-65

Stretch of Highway	Weighted Average Suitability Index[1]
I-70 (West of Indianapolis)	1.523
I-70 (East of Indianapolis)	2.130
I-65 (North of Indianapolis)	2.143
I-65 (South of Indianapolis)	3.134

[1]Scale: 1 (highest suitability)–5 (lowest suitability).

Both stretches of I-70 showed the lowest numbers, meaning the highest suitability compared to these in I-65. I-70 constitutes one of the heaviest traveled roadways in America, and commercial truck volumes have increased at higher rates compared to private automobile volumes. Furthermore, the 4-State Coalition continuously reviews I-70 developments and opportunities for advanced dedicated truck lane improvements (e.g., truck platooning). Hence, this corridor plays an important role and has the potentials to be used for the ER technology deployment, since it will also be part of the Alternative Fuel Corridor Program. The deployment of ER technology in Indiana would be more cost effective if the technology is a part of a larger system or if it is located at strategic places to attract federal funding to overcome the cost of research.

In the base case, there are segments on I-70 that stood out in terms of their suitability. Table 3.3 shows the locations, length and reasons for the suitability of the specific segments.

Depending on the goals of the individual transportation agency, there may be multiple solutions to the problem of deploying this new technology. Therefore, the problem of locating ERs does not have a straightforward solution and why a sensitivity analysis is critical for making judgments about the importance of certain criteria. The sensitivity analysis showed that the main criteria that affect the results are truck traffic and the distance of ERs from airports, ports, and EV charging stations. The results are presented in Table A.2 of the Appendix. Figures A.5–A.9 in the Appendix show the corresponding maps when considering a 0.7 weight for each of these four criteria.

For the criteria that greatly affect the results, a trade-off analysis could be undertaken to determine their priority. An example of such a trade-off analysis, especially when ER technology is in the initial stages of deployment, would be between the cost effectiveness of the ER locations and the potential of the locations for

TABLE 3.3
Most suitable segments on I-70 (base case)

Segment Location	Length (miles)	Comments
SR 3 to Wilbur Wright (Exit 123)	7.6 miles	The segment is characterized by the highest truck traffic compared to all the other segments of the road network and is at a distance from EV charging stations.
Mt. Comfort to SR 9 near Greenfield	10 miles	The segment has high truck traffic, is at a distance from EV charging stations and will undergo pavement replacement.
SR 39 to SR 267	7 miles	The segment has high truck traffic, is located near the Indianapolis airport and near intermodal facilities. Additionally, preservation/maintenance activities are planned for this segment.
SR 267 to Ameriplex Parkway	2.5 miles	The segment has high truck traffic, is located near the Indianapolis airport and near intermodal facilities. Additionally, preservation/maintenance activities are planned for this segment.

providing the kind of public exposure that could later increase the system's adoption (e.g., by locating the technology close to airports or ports). The analysis that will follow (Task 4) will shed light on the construction cost estimate of constructing charging lanes.

This analysis entails certain limitations. ER technology is part of an innovative system that has not yet been practically and widely implemented, and therefore experts' opinions are necessary to determine the weights of the criteria and the final ER locations. To avoid any subjectivity on this matter, the analysis presented herein assumed equal weights for the criteria involved and assessed the effects of the uncertainty regarding the weights through a sensitivity analysis. In addition, the criterion of distance from existing substations was not used because no relevant data were publicly available. It should be noted, though, that if the ER system were to be implemented on a wide scale, investments might be made in new substations that are solely dedicated to satisfying the power requirements of ERs.

3.2 Corridor Level Analysis

3.2.1 Substation Selection Algorithm Overview

In this research, an algorithm was derived to answer two issues that will likely arise in the planning stage of ER development. The first is to what degree the existing power infrastructure can be used to support a dynamic wireless charging system. The second is where new substations are needed to support the expanding market penetration. To begin to address these issues, a substation selection algorithm was developed. This algorithm accepts as input the locations and power levels of substations within 10 miles of roadway segments of interest, the roadway segment traffic from WIM scales, and the power required by the vehicles. The power of the vehicles is readily obtained from a vehicular power model that relates power being consumed by a vehicle to its mass and speed. From these inputs, the algorithm determines the segments of the road that can be powered and the substations that are used to provide power.

3.2.2 Substation Selection Algorithm Steps

It is first assumed that the roadway under analysis can be discretized into segments. A segment is defined as any continuous length of road. In this case, segments are defined by the TMC segment standard. As described earlier in the report, to energize a segment requires the placement of coils within the roadway. The power required and location of each segment is accepted as an input. The algorithm also requires the location and available power capacity of the substations. For initial algorithm development, this data was obtained for substations around the I-65 corridor south of Indianapolis from Hoosier Energy (I-65 S). Segment data for I-65 S was obtained from INDOT. This data was made available in Microsoft Excel files which were readily accessed using MATLAB (language used to develop the algorithm).

Based upon the segment and substation longitude and latitude, the minimal distance from each substation to each segment is calculated assuming that Earth's curvature is negligible. Next, it is assumed that each substation, assuming it has sufficient power available, provides power to the segment closest to it. The closest segments are referred to as anchor segments. The ability of a substation to provide power to additional segments beyond the anchor segments is then evaluated by considering the respective substation available power. If a substation can supply the power required, its geographical coverage continues to expand. The potential coverage range is then evaluated for each substation. Once coverage ranges are determined, any overlap of substation coverage is evaluated. If multiple neighboring substations can provide power to the same segments, the substation that has the highest power/cable distance ratio (referred to as Distance Specific Power) is selected. Here, highest power refers to the total power provided to the roadway by the substation.

3.2.3 Algorithm Findings

The substation selection algorithm was used to evaluate the ability of the existing power system to cover dynamic EV charging along I-65 from Indianapolis, IN toward Louisville, KY. To perform the analysis, it was assumed that the roadway was constructed to provide a power of 280 kW at the input to each transmitter, which is sufficient to maintain the state of charge of class-9 trucks traveling at 65 mph (refer to Section 4). The algorithm was used to evaluate the percent of the roadway that existing substations can support under low (20%)-, medium (50%)-, and high-penetration (100%) levels of EVs in the marketplace. It is noted here that only the Hoosier Energy substations were included in the analysis, and thus this likely represents a worst-case coverage ability. The results are shown in Table 3.4.

It can be observed that for low penetration levels, roughly 50%–60% of the I-65 northbound segments could be energized to the level needed to support class-9

TABLE 3.4
Percent of roadway electrified using existing substations

EV Penetration	I-65S Northbound (NB) Coverage	I-65S Southbound (SB) Coverage
Low	50%–60%	30%–40%
Medium	25%–30%	10%–15%
High	15%–20%	5%–10%

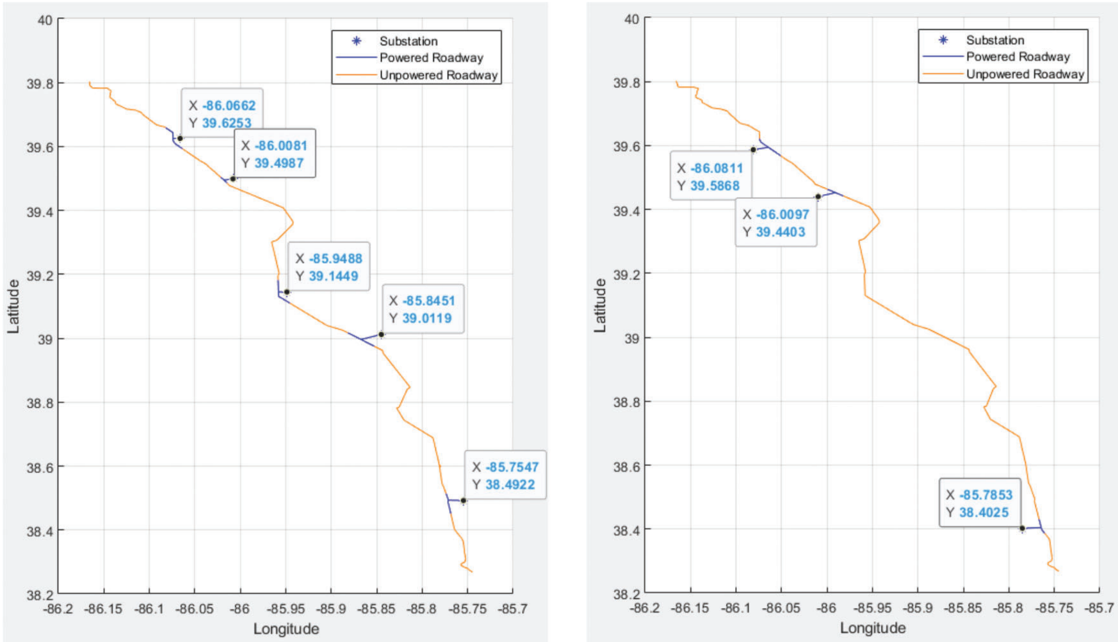

Figure 3.3 I-65 S roadway segments that can support charging at high EV penetration using existing substations (northbound is shown on left, southbound on right).

trucks. This is reduced to only 15%–20% at high market penetration levels. Of note is that the coverage numbers are lower for I-65 southbound. This is largely due to a difference in the traffic volume of the north- and south-bound lanes. The respective segments covered for the north- and south-bound lanes at the highest EV penetration are shown in Figure 3.3. Although the addition of substations from other utilities (i.e., Duke Energy) will increase the coverage, it is likely that new substations will be required to support commercial EVs as market penetration expands.

4. DEVELOPMENT AND DESIGN OF A TEST BED

4.1 Interface with Power Utility and Charging Architecture

Portions of this section are published in: Haddad, D., Konstantinou, T., Pasad, A., Hua, Z., Aliprantis, D., Gkritza, K., & Pekarek, S. (2019). Data-driven design and assessment of dynamic wireless charging systems. *2019 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer (WoW)*. https://doi.org/10.1109/WoW45936.2019.9030612

Many challenges need to be addressed in developing a Dynamic Wireless Charging system (DWC), including design of the components, design of the roadway, and charging control. Understanding and addressing the impact of the DWC on the power distribution system is key to the integration of this technology in Indiana.

An estimation of the power needs of the wireless charging system was calculated by developing a design for a suitable road segment in Indiana. In particular, the I-70 corridor was selected as a candidate corridor for this system, due to its high truck traffic and potential to be an alternative fuel corridor, among other reasons. The objective is to design a DWC power system that is capable of powering commercial class-9 trucks (as defined by the Federal Highway Administration vehicle classification system; FHWA, 2014), assuming 100% penetration level and purely electric drivetrains. Trucks typically operate on fixed routes, so they are likely to be early adopters of DWC infrastructure. Another motivation for heavy-duty trucks to adopt the DWC system is that battery energy storage requirements for long-range heavy-duty powertrains are substantial, thus leading to high costs (Chen et al., 2016). DWC can help alleviate this concern.

4.1.1 Data and Methods

Weigh-In-Motion (WIM) data between 2017 and 2019 was obtained for the 7.6-mi segment of U.S. interstate I-70 between SR 3 to Wilbur Wright through the Traffic Count Database System of INDOT. This segment has high truck traffic and has been identified as part of an alternative fuel corridor (FHWA, 2021; INDOT, 2019). As such, the focus of the analysis was on vehicle class 9, which dominates the vehicle mix. The difference in the average annual daily traffic across the two directions of the segment is lower than 2%. As such, the analysis in this section focuses on the west-bound direction of the study segment.

Statistical analysis is performed on the traffic data. Hourly distributions of speed, weight, power, and headway are used to estimate the power requirement of a representative class 9 vehicle. Furthermore, the distributions are used to develop a data-based stochastic traffic flow model, which enables us to conduct a series of studies on the power distribution system.

The speed data showed that the average velocity of class 9 trucks is very close to 65 mph, with relatively small standard deviation. This is likely due to the use of governors to limit vehicle speed and the fact that the truck differential legal speed limit is 65 mph for rural interstates in Indiana. The weight data showed that the upper bound is 80,000 lbs, which is the legal limit on most US interstates.

The power distribution is obtained from the data by first calculating the traction power at the wheels of each vehicle using the weight and speed data from the WIM station. Other required vehicle parameters are randomly sampled from a suitable range for class 9 trucks for each vehicle. The total power that the on-board electrical source needs to supply is calculated by assuming an efficiency of around 92% of the drive train and an auxiliary power consumption that is logged from a random distribution with a mean of 7.5 kW and a variance of 1.5 kW. Statistics of the electrical power required at the truck input as function of velocity are shown in Figure 4.1. The box contains 50% of data, where the red line represents the median, and whiskers contain roughly 99% of the data. The red crosses represent outliers. Also shown in black is the average receiver power (assuming perfect lateral alignment between receiver and transmitter), so that one obtains a sense of the DWC capability. For example, this result could be used for estimating battery charge/discharge when moving at speeds other than nominal.

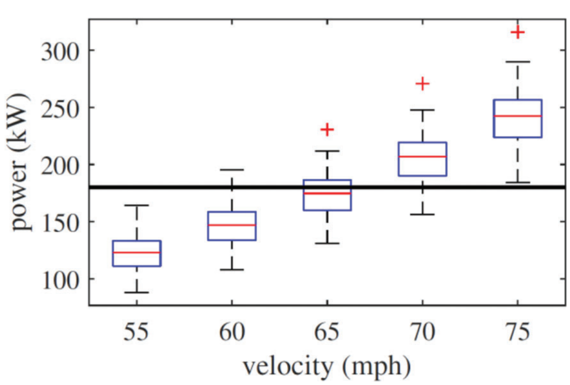

Figure 4.1 Statistics of electrical power required as a function of velocity and average truck receiver power.

In addition to power level estimation, the traffic data analysis is used to parameterize a stochastic traffic flow model. This model accepts as an input the traffic count and velocity, and outputs a stream of moving trucks based on the statistics of the headway.

Figure 4.2 shows the proposed layout of the DWC system. The proposed length of the transmitters is l_{Tx} = 25 m, with a spacing of d_{Tx} = 5 m. The proposed receiver length is l_{Rx} = 3 m. The road segment being considered for single-lane DWC has a total length of 7.6 mi. To cover the entire length of the segment, 408 transmitters are required. The rated transmitter power is determined by the traffic data using Equation 4.1 (Haddad et al., 2019).

$$P_{Tx} \geq \frac{P_{elec,nom}}{\eta_x}\frac{l_{Tx}+d_{Tx}}{l_{Tx}} \qquad \text{(Eq. 4.1)}$$

where η_x is the transmitter-to-receiver efficiency and is assumed to be 75%, and $P_{elec,nom}$ is the 180 kW, which is the nominal electrical power that was selected based on the statistical analysis of the traffic data. This results in a rated transmitter power of 288 kW.

A distribution substation was located at a linear distance of 2.25 mi from the segment in this study. The substation was located at 5.8 mi from the start point of the segment. For the grid interconnection design, a 20 MVA HV/12.45 kV transformer is added to the existing substation.

Figure 4.3 shows the proposed layout of the distribution network.

Each power transmitters that is embedded within the roadway is connected to an inverter. Four inverters are connected to a single transformer-rectifier (TR) unit. The TR unit consists of a pad-mount low-voltage transformer and an active front-end rectifier. They supply power via dc cables to the inverters that are placed near the transmitters. Four main feeders supply the TR units distributed along the road segment. Each main feeder is intended to provide power to approximately 2 mi of roadway (roughly 25 TR units). An underground cable distribution is used. Cables with length shorter than 4.5 mi have cross-section of 250 kcmil (thousands of circular mils, 1 kcmil = 0.5067 mm^2), while longer cables have 500 kcmil cross section to reduce voltage drops.

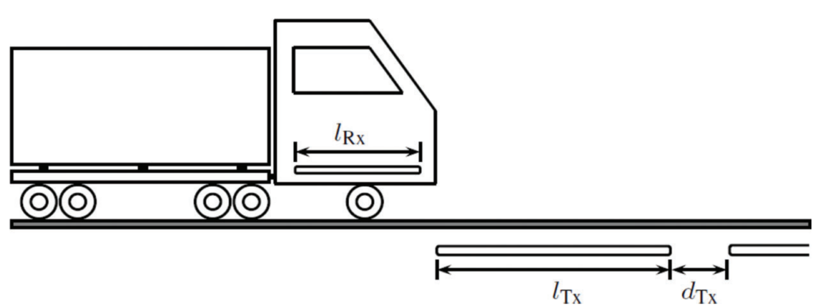

Figure 4.2 DWC system layout.

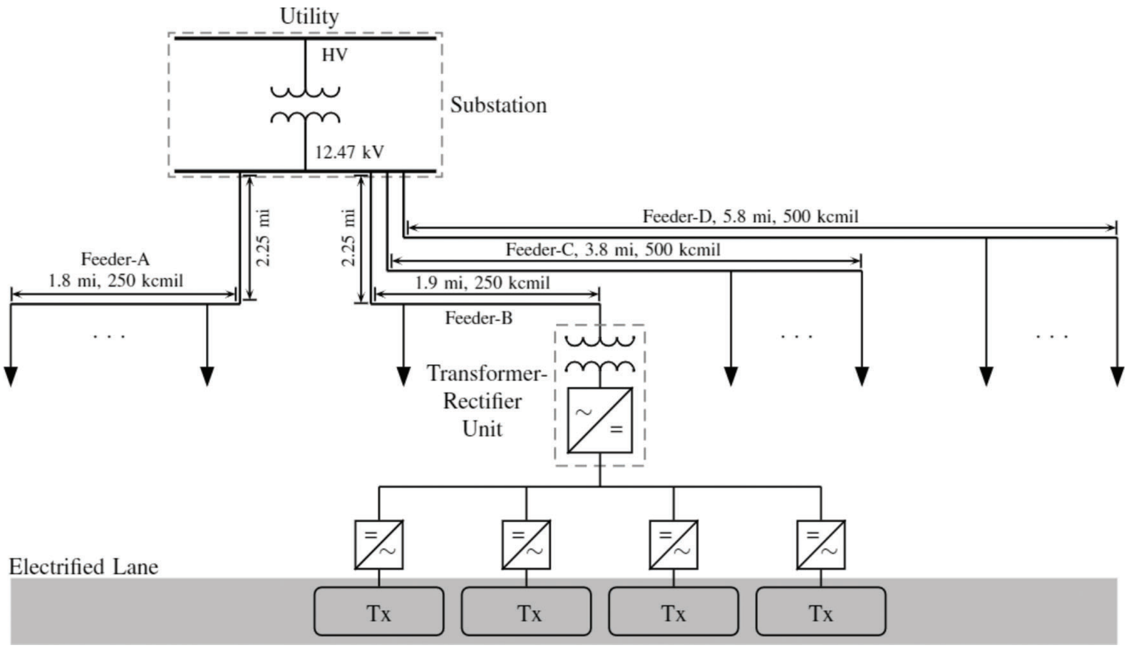

Figure 4.3 Layout of the power distribution network.

4.1.2 Findings

As mentioned in the previous section, a data-based stochastic traffic flow model is developed, which enables us to conduct a series of studies on the power distribution system. A fleet of vehicles is simulated for a representative high-traffic condition based on the statistical analysis outcomes, with a class 9 traffic volume of 450 trucks/hour and a velocity of 65 mph. The headway between consecutive vehicles is sampled from statistical data analysis outcomes. This traffic is translated into electrical load using the charging system design described in Section 4.1.1.

Multiple penetration levels of electrified trucks are considered for the analysis (25%–100%). Figure 4.4 shows the aggregate power demand at the substation for a 15-min period. For 100% penetration, an average load of 16.9 MW (2.2 MW/mi) is predicted. An average power consumption of 4.4 MW (0.6 MW/mi) is obtained for 25% penetration. For understanding the magnitude of the power requirement, Figure 4.5 shows the equivalent of the mentioned power levels in number of households. An estimated household consumption of 1 kW is used.

Figure 4.6 shows a 10-s interval for the case of 100% penetration. Significant power ramp rates that can reach as high as $\pm$15 MW/s can be observed.

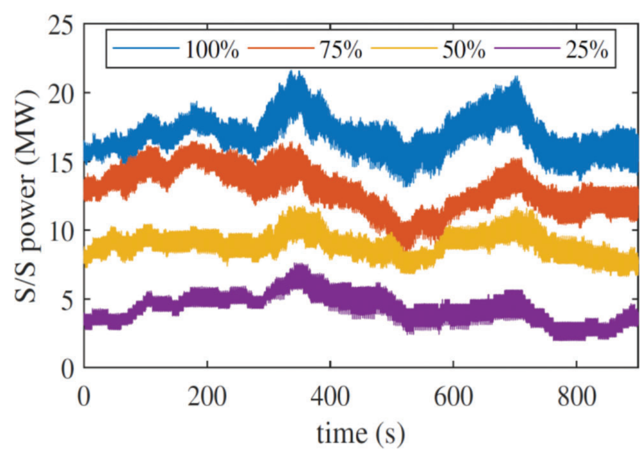

Figure 4.4 Power demand at the substation transformer for four penetration levels (25%–100%).

4.2 On-Board Power Electronics and System Design

4.2.1 Data and Methods

The design of the charging system entails the selection of all the components shown in Figure 4.7. This includes the transmitter and receiver core geometry and dimensions, the compensation circuit components (L and C values shown to the left and right side of the transmitter/receiver) and the power electronics involved in the DC-AC and AC-DC power conversion process.

Prior to the design process two important decisions were made:

1. Selection of the design variables: The design variables are parameters of the system which are varied to arrive at an optimal design. In the case of the charging system design these variables were selected to be the geometrical dimensions of the transmitter and receiver systems and the electrical system parameters.
2. Selection of the design objectives: In the case of the charging system design two design objectives have been selected, minimize system mass and minimize system loss. The mass includes the mass of the transmitter, the receiver, the compensation circuit components and the

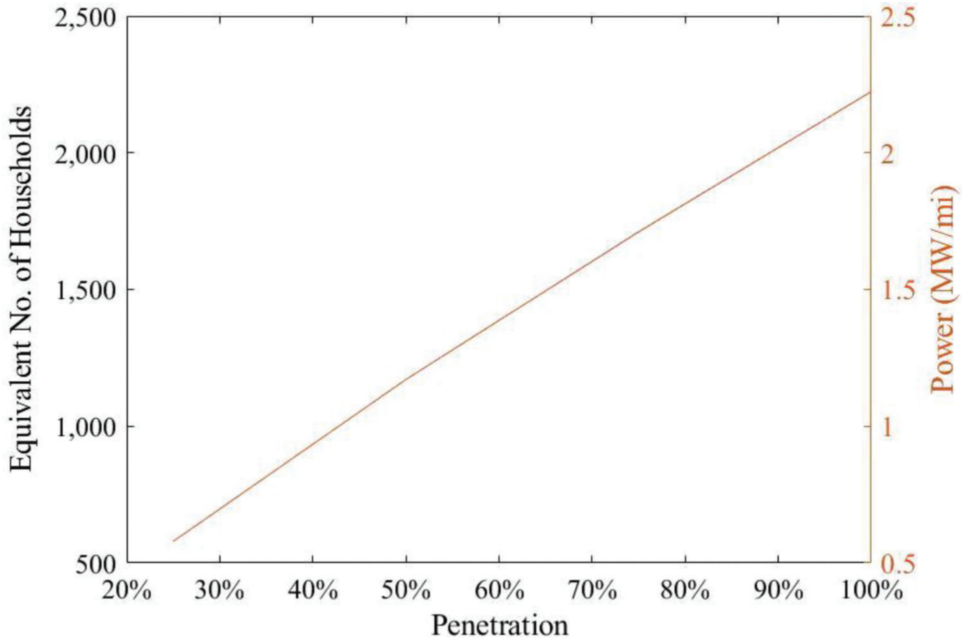

Figure 4.5 Power requirement in an equivalent number of households.

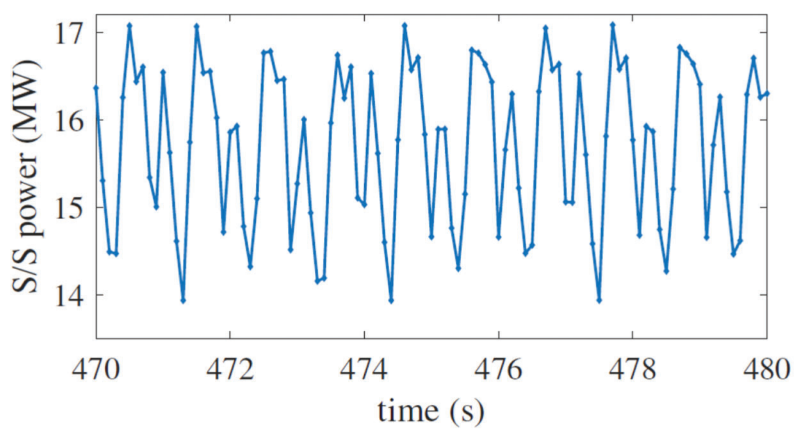

Figure 4.6 Substation power waveform (100% penetration).

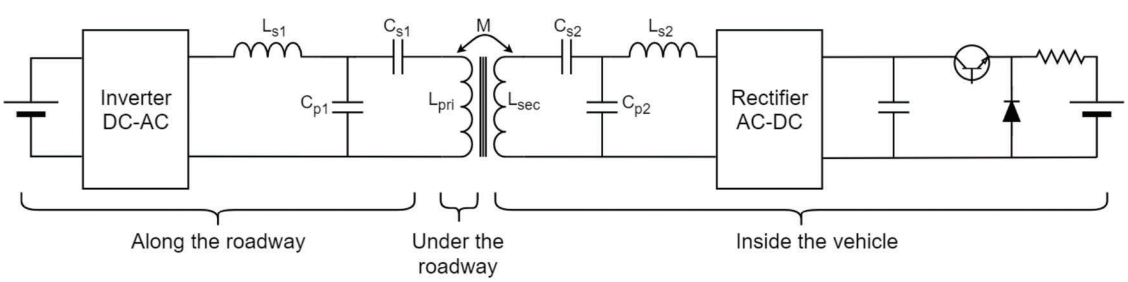

Figure 4.7 Charging system.

power electronics. The reason for including the mass of the receiver is because it adds to the mass of the vehicle and hence to the power requirement. The mass of the transmitter is related to the cost of the transmitter core material and the conductors. Therefore, by reducing the mass of the system we will be able to bring down the cost of the system and thus, the power requirement of the vehicle. Minimizing power loss reduces the necessity to deal with heat generated by the conversion process and reduces the energy required from the utility supply. In this research, the power loss calculated includes the loss in the transmitter/receiver and the power converters.

4.2.1.1 Power Electronics. For power to be transmitted through an air gap, from the transmitter to the receiver, the electrical energy must be converted from the direct current (DC) form to an alternating current (AC) form. Furthermore, in order to charge the on-board battery, the electrical energy in the AC form must be converted to the DC form. This conversion, commonly known as DC-AC and AC-DC conversion, is accomplished using power electronics converters. The functioning of an inverter is shown in Figure 4.8. In this figure a DC voltage of 500 V is given as input to the inverter. The switching action of the power electronic components within the inverter converts this constant voltage waveform into an alternating waveform the value of which oscillates between +500 V and -500 V.

To calculate the mass and the power loss of the power electronic converters, metamodels have been implemented which take as input the input DC voltage and output AC current and provide the expected mass/volume required and the respective power loss of the AC-DC conversion. The metamodels for both the inverter and the rectifier have been developed based on the data of a commercial 750 V, 200 kW inverter 50 kHz (vendor is P.C. Krause and Associates) that utilized a Wolfspeed CAS300M17BM2 switching module. The mass of the switching module, connectors, heat sink, and EMI filter were characterized by their research engineer (Nick Benavides). These were used within our designs by first determining the number of the Wolfspeed switching modules that would be needed to handle the current required to supply the transmitter (and on the receiver end the current to the battery). Subsequently, the mass then scaled with the number of modules. The EMI filter scaled directly as a function of the number of modules and inversely with the switching frequency (specifically by multiplying by the mass of the EMI filter by 50 kHz/switching frequency). The switching and conduction loss were determined from the data sheets of the Wolfspeed CAS300M17BM2 modules, which provides the on-state resistance and the energy loss per switching event.

4.2.1.2 Compensation Circuit Components. The compensation circuit, which consist of inductors and capacitors between the power electronics converter and the transmitter/receiver windings. The compensation circuit components are paramount in eliminating the electrical harmonics generated by the power electronic converters and also, ensuring that the inverter and rectifier see near-unity power factors on their ac-sides. In simpler terms, the compensation circuit helps shape the current or voltage waveform which is supplied as input to the transmitter/receiver. Figure 4.9 describes this functionality. The square wave is representative of

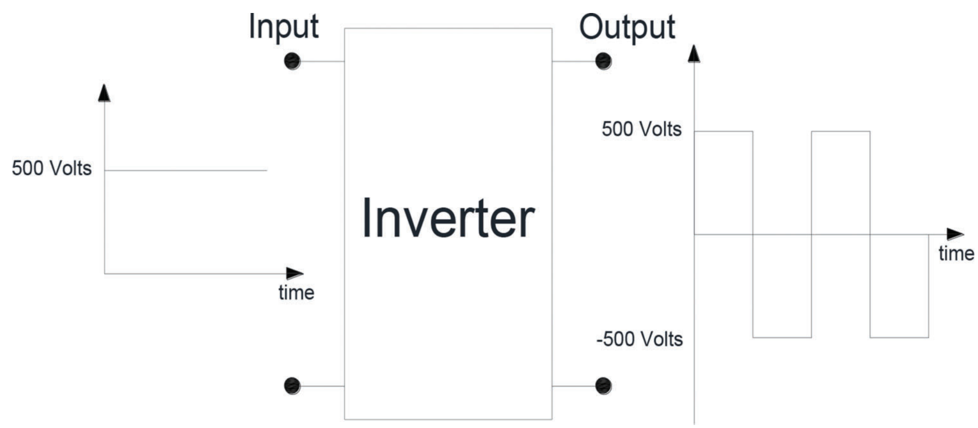

Figure 4.8 Inverter input/output.

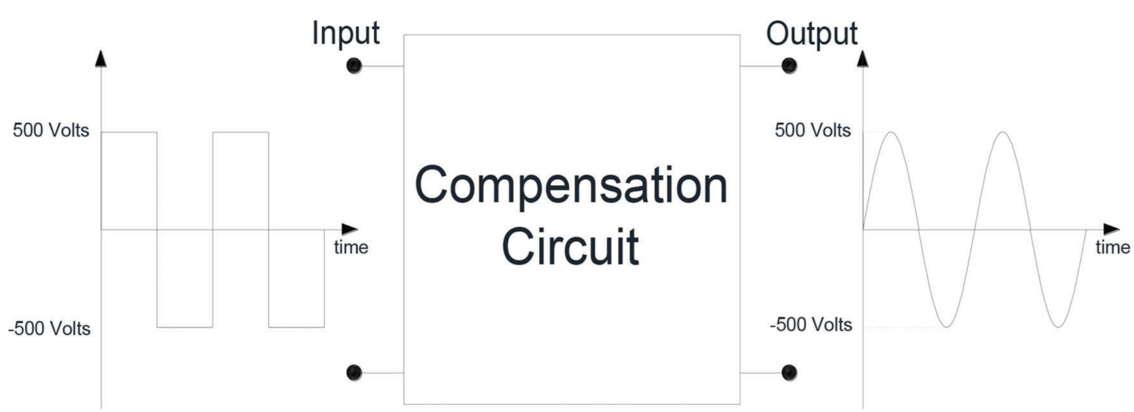

Figure 4.9 Function of compensation circuit.

the voltage which is available at the output of the power electronic converter. This square wave is fed as input to the compensation circuit and one receives as output a sinusoidal waveform which is then supplied to the transmitter winding.

The compensation circuit is composed an inductor and a capacitor. The calculation of the mass and power loss occurring within the compensation circuit components each of these components is described next.

1. Capacitor

The capacitor mass and power loss are calculated by employing metamodels. To generate these metamodels polypropylene capacitor data is obtained from Vishay Intertechnology (2019) data sheet). The metamodel used for estimating the capacitor mass has the following form.

$$Mass = f_M(C) = \alpha * C + \beta \quad \text{(Eq. 4.2)}$$

To calculate the power loss occurring within a capacitor two quantities are required, namely the current passing through the capacitor and the effective series resistance (ESR). The current passing through the capacitor is readily calculated using circuit laws. In order to estimate the ESR of a capacitor another metamodel is employed which has the following form.

$$ESR = f_{ESR}(C) = \frac{\gamma}{C} + \delta \quad \text{(Eq. 4.3)}$$

The power loss is then calculated as follows.

$$Power\ Loss = I^2 * ESR \quad \text{(Eq. 4.4)}$$

The description of the variables in Equations 4.2–4.4 is provided in Table 4.1.

2. Inductor

The metamodel for mass and power loss described of the inductor is based upon those developed in the literature for DC inductors (Sudhoff et al., 2013) and is given in Equation 4.5 and 4.6 respectively.

$$Mass = c_M E_{mi}\, \Pi_{k=1}^{7} \left(J_{pk} E_{mi}^{1/3} + b_{M,k}\right)^{n_{M,k}} \quad \text{(Eq. 4.5)}$$

$$PowerLoss = 0.5 \cdot c_P E_{mi}^{1/3}\, \Pi_{k=1}^{7} \left(J_{pk} E_{mi}^{1/3} + b_{P,k}\right)^{n_{P,k}} \quad \text{(Eq. 4.6)}$$

where,

$$J_{pk} = \sqrt{2} \cdot J_{rms} \quad \text{(Eq. 4.7)}$$

TABLE 4.1
Capacitor metamodel variable description

Variable	Description
C	Capacitance of the capacitor
ESR	Effective series resistance
I	Current flowing in the capacitor
α, β, γ, δ	Metamodel parameters

$$E_{mi} = 0.5 L i_{pk}^2 \quad \text{(Eq. 4.8)}$$

$$c_M = 5.9851 \quad \text{(Eq. 4.9)}$$

$$c_p = 1.1021 \times 10^{-5} \quad \text{(Eq. 4.10)}$$

and coefficient values are provided in Table 4.2.

4.2.1.3 Transmitter and Receiver. The Double D type transmitter geometry was selected for design and the receiver has a U- shaped geometry. The material used for the transmitter and receiver cores is the magnetizable concrete developed by MAGMENT. The transmitter and receiver windings are assumed to be created using Litz wire turns which aids in mitigating the skin effect losses prominent in high frequency applications. The mass of the transmitter and the receiver consists of two components—the mass of the core and the mass of the winding. The mass of the core can be calculated by multiplying the volume of the core by the density of the material which is available from MAGMENT (n.d.). The mass of the winding is calculated by multiplying the total length of the conductor by its mass per unit value given in the catalog (New England Wire Technologies, n.d.). To calculate the power loss occurring in the core finite element analysis of Maxwell's equations is performed.

4.2.1.4 Optimization. To arrive at designs that minimize mass and loss, genetic optimization is employed. In this optimization technique the design variables are specified along with constraints that are imposed. The constraints imposed in the optimization belong to two categories:

1. Geometrical Constraints: Geometrical constraints are constraints which limit or enforce certain conditions on the dimensions of the transmitter and receiver components. For example, the width of the transmitter core base is set to be less than the 12 ft.
2. Electrical Constraints: Electrical constraints relate to limits placed on electrical quantities such as current and voltage values. For example, the voltage between two points should be less than 1.2 kV.

Figures 4.10 and 4.11 show the geometrical variables associated with the transmitter and receiver. Table 4.3

TABLE 4.2
Inductor metamodel model coefficients

k	$b_{m,k}$	$n_{m,k}$	$b_{p,k}$	$n_{p,k}$
1	0	0.24700	0	0.54482
2	100.05	0.24673	1.1658×10^3	0.25254
3	100.05	–1.3215	1.1658×10^3	0.17114
4	3.4677×10^6	–1.2423	1.1659×10^3	0.24906
5	8.2537×10^6	2.4809	5.1412×10^4	–0.15241
6	7.3079×10^7	–2.0633	4.4344×10^5	0.52755
7	1.0430×10^8	1.5530	1.2330×10^6	–0.59614

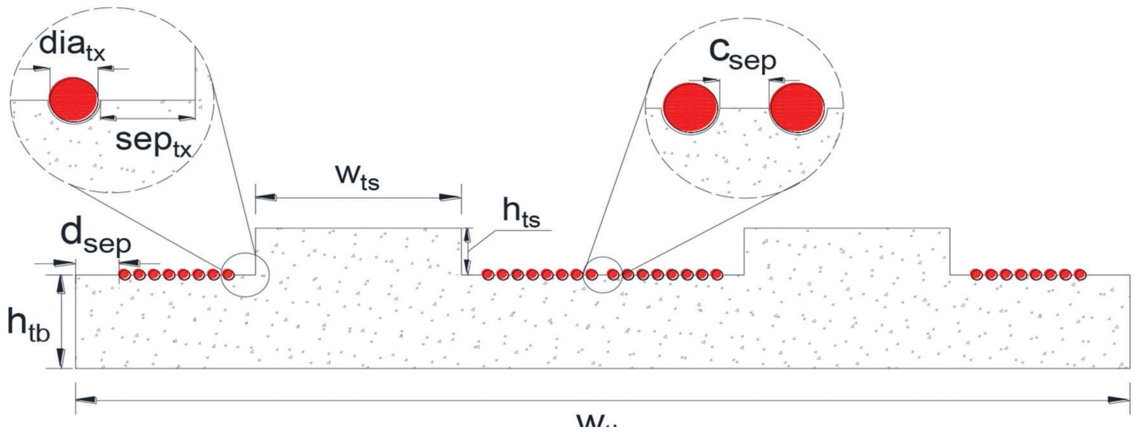

Figure 4.10 Double D transmitter.

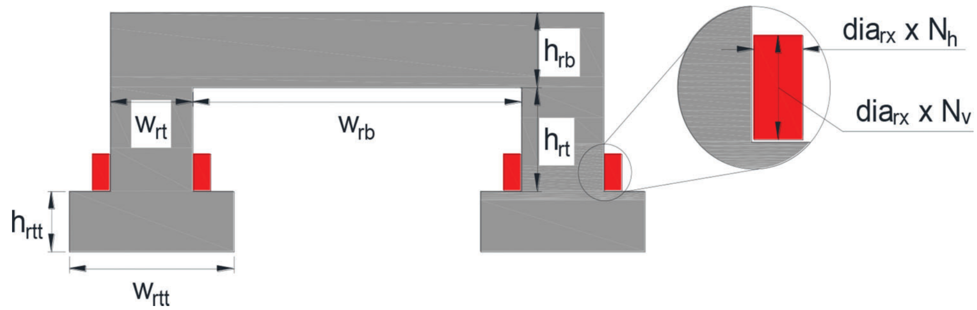

Figure 4.11 Double D receiver.

TABLE 4.3
Design variables

Variable	Description	Type
h_{tb}	Transmitter base height	Geometrical
d_{sep}	Distance between outside edge of transmitter and winding	Geometrical
sep_{tx}	Separation between winding and transmitter stub	Geometrical
w_{ts}	Width of the transmitter stub	Geometrical
h_{ts}	Height of the transmitter stub	Geometrical
c_{sep}	Separation between center windings	Geometrical
dia_{tx}	Diameter of transmitter winding conductor	Geometrical
$sratio$	Ratio of conductor diameter to slot diameter	Geometrical
w_{rtt}	Width of the receiver core tooth tip	Geometrical
h_{rtt}	Height of the receiver core tooth tip	Geometrical
w_{rt}	Width of the receiver tooth	Geometrical
h_{rt}	Height of the receiver tooth	Geometrical
w_{rb}	Width of the receiver base	Geometrical
h_{rb}	Height of the receiver base	Geometrical
dia_{rx}	Diameter of receiver winding conductor	Geometrical
Nh	Number of receiver windings turns oriented horizontally	Electrical
Nv	Number of receiver windings turns oriented vertically	Electrical
f	Frequency of the electrical system	Electrical
I_{pri}	Transmitter winding current	Electrical

and Table 4.4 list the design variables and the constraints imposed in the optimization respectively.

4.2.2 Findings

An initial optimization was performed with all the design variables mentioned in Section 4.2.1. The optimization of the entire dynamic wireless power transfer (DWPT) system from the DC supply on the transmitter side to the rectifier and battery at the receiver end was performed with the aid of GOSET using a generation size of 700 and population size of 200. The desired output power of the design was set at 280 kW and the input voltage at the transmitter end was set at 500 V DC.

TABLE 4.4
Constraints

Constraint	Description
$h_{tb} \geq 0.5 \times dia_{tx} \times sratio$	The height of the transmitter base should be greater than the radius of the slot radius.
$w_{tb} \leq 3\ meter$	The width of the transmitter should be less than 3 m.
$(h_{tb}+h_{ts}) \leq 3\ meter$	The total height of transmitter should be less than 30 cm.
$w_{rtt} \geq w_{rt} + (2 \times N_h \times dia_{rx})$	The receiver winding must fit on the receiver tooth tip.
$(h_{rt}–h_{rb}) \geq (N_v \times dai_{rx})$	The receiver winding height must be less than the window between the receiver toot-tip and base.
$I_{pri}/(0.25 \times \pi \times dia_{tx}^2) \leq 7A/mm^2$	The current density in the transmitter winding is less than 7 A/mm^2.

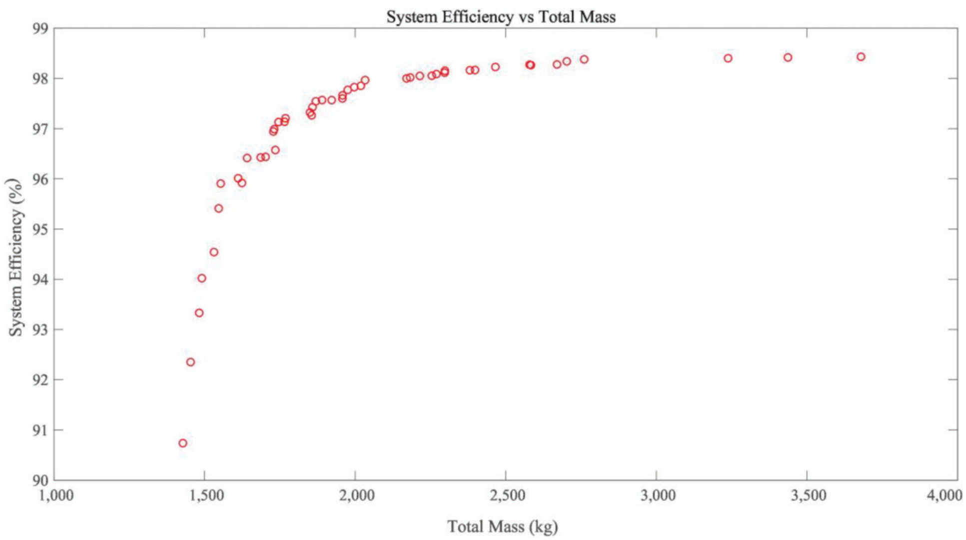

Figure 4.12 Total power loss vs. total mass.

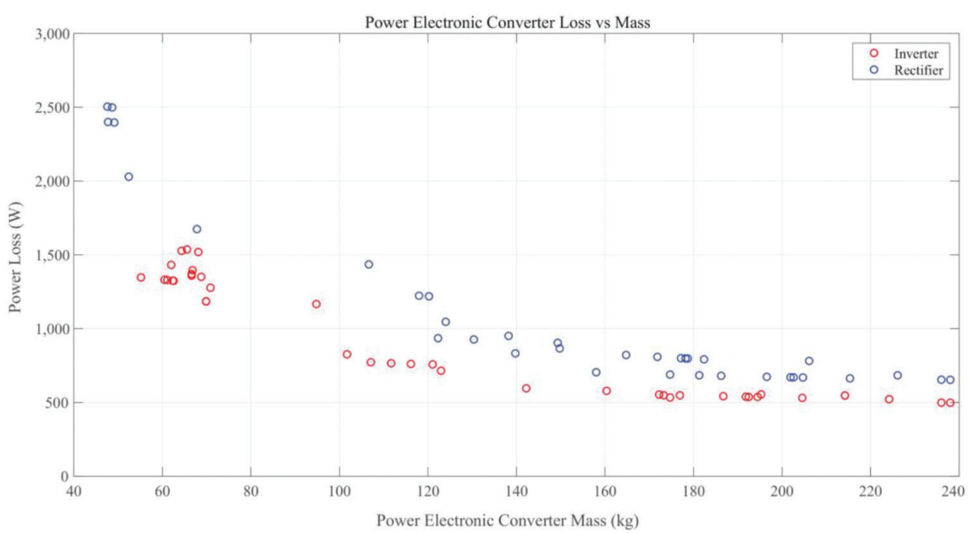

Figure 4.13 Power electronics converter loss vs. mass.

The optimization has provided multiple candidate designs. Figure 4.12 provides the Pareto-optimal front the power loss and the total mass of the system varies. It can be observed that as the mass increases the system efficiency increases. This is a trend observed in most electromagnetic systems. It should be noted that here the power loss includes the loss occurring within the core of both the transmitter and receiver and the loss occurring within the power electronic converters.

Figure 4.13 provides an idea of how the power loss occurring within power electronics converters varies with the mass of the converters. A similar trend exists

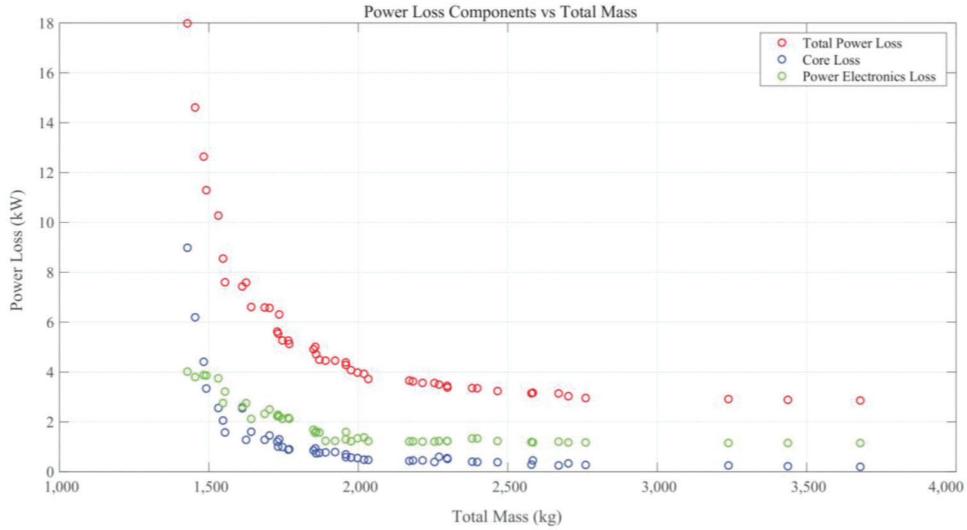

Figure 4.14 Power loss components vs. system mass.

for the power electronic converters—as the mass of the converter increases the power loss decreases. Although this can be related, it must be kept in mind the deciding factor for the converter loss is the frequency at which the system is operated. It can be observed that there is a significant gap in the plot for converter masses ranging from about 55 kg to 100 kg. The reason for this split is that the optimization chose frequencies close to 60 kHz and 20 kHz. This resulted in the clustering of the results at different parts of the graph.

Figure 4.14 shows the variation of the power loss components with the system. One of the important observations from the figure is that the power electronics loss dominates the core loss. This means that the systems efficiency can be significantly improved by using efficient power electronic converters. Figure 4.14 gives a clear idea of the variation of the core loss with mass of the system. The major contributor to the system mass is the transmitter and receiver core. Hence the system mass may be thought of as a representation of the core mass. It is evident from Figure 4.14 that as the mass of the core increases the core loss decreases. This is because the core loss is related to the magnetic flux density within the core. With an increase in the mass of the core the flux density in the core decreases there by resulting in a lower core loss.

5. LOCALIZED ELECTRIC ROAD CONSTRUCTION COST ESTIMATION AND FINANCIAL ANALYSIS

One of the major concerns for the ER technology is its cost. The implementation cost of ERs may depend on a variety of factors such as the type of installation or accessibility to the power network, and materials of the charging infrastructure, which are part of the civil and electrical infrastructure system cost. In general, there is limited literature about the costs of each pay-item associated with the technology; in most studies, the total cost of the ER infrastructure is only reported (see Section 2.3). Additionally, there is currently a limited number of implemented DWC systems, other than test beds. In this chapter, information about the different types of roadway ER installation methods and associated costs found in the literature are discussed. Focus is given the cost of installing the required electrical infrastructure for charging along with the supporting power system. Economic viability of the technology is analyzed for a case study on I-65 S.

5.1 Civil Infrastructure Cost

Different types of potential road construction methods were found in the literature and examined in terms of their advantages and disadvantages, given the project purposes. There are three main types of installation methods for the ER technology: trench-based construction method, full lane reconstruction method and full lane prefabricated construction method, as discussed next (de Blas, 2017; Highways England, 2015).

- *Trench-based construction*: In this method, a trench is excavated in the roadway for the installation of the charging coils. Trench based installations are typically used in embedded rail systems and by utility companies in existing roadway pavements. This installation method is quick and cost effective, with minimal impact on the structural integrity of the pavement, leading to lower long-term maintenance costs. However, there may be durability issues since this method may cause reflective cracking at the pavement surface or at the transverse joints where the power is supplied from the roadside equipment.
- *Full lane reconstruction*: In this construction option, the existing pavement is entirely removed, and the charging infrastructure is installed in the new pavement at the appropriate stages; the DWC components and the related connection pipework are delivered to the site and installed as part of the pavement construction process;

the charging infrastructure can be easily installed. However, it is more expensive and time consuming compared to the trench-based method unless it is conducted as part of a larger project.

- *Full lane prefabricated construction*: This construction method is an alternative to the full lane reconstruction and involves removing pavement sections from existing pavements and replacing them with prefabricated full lane width sections that contain the complete DWC system. Prefabricated concrete pavement has been used as a general construction approach, although not in combination with DWC units. Among the various advantages of this method are the accelerated construction period, factory construction quality and increased durability that reduces the needs for future maintenance. While this method involves high capital costs, there would be savings in traffic management costs with the only major concern being the potential disruption caused by transporting the prefabricated sections to the site. Additionally, economies of scale may be achieved when this construction method is adopted as part of a larger pavement replacement project planned for implementation irrespective of the ER construction.

All methods described above entail certain advantages and disadvantages. The identification of the most appropriate method will require trials. An exact method of electrical system installation does not yet exist and testing and validation are required. It is important to mention that the prefabricated construction option and the use of a precast system would allow for trial and error during the slab fabrication process. Without proper care, the field installation of charging units will require special attention during construction to ensure adequate pavement quality. Using precast technology provides better construction techniques to ensure proper material consolidation around embedded charging systems, as compared to field constructed slabs. Table 5.1 shows examples of cost estimates for a typical precast panel. Variations in these costs may exist depending on the project size and other logistics.

To calculate the total civil infrastructure cost associated with a full lane prefabricated construction, two components were considered. The first component is the cost of precast concrete panels ($2,464,000/lane-mile) that assumes $350/sy for the cost per precast panel and 12 × 15 ft concrete panels. Second, the construction will also involve the cost of installing the charging pads in the concrete panels ($619,801/mile). This includes the cost related to the following activities: installation of the prefabricated coil into form, conduit and other miscellaneous materials, interconnection of wiring of slabs and material handling and packaging. This cost estimate was provided by a major infrastructure firm as part of a related project (Zane et al., n.d.). Therefore, the total initial construction costs for the prefabricated installation method amounts to $3,083,801/lane-mile. Note that this estimate represents an upper bound of the civil infrastructure costs as it is possible to combine the use of precast panels for ER segments with in-situ installation methods for segments of the roadway that are not electrified.

The implementation of the charging units inside the pavement of an existing roadway should be carried out jointly with construction or maintenance operations, for cost-efficiency reasons (Bateman et al., 2018; FABRIC, 2014b), including savings in terms of the management of traffic. High intensity pavement work types, such as a total pavement replacement or new road construction, are more appropriate than low intensity work types for inclusion of the DWC system. In this case (where installation of charging units is part of another larger pavement project), INDOT reported the normal cost for the basic slipform paving is approximately $40–$50/sy and for normal concrete patching around $200/sy. Additionally, based on INDOT's plans for future work activities, high intensity pavement work is scheduled for the near future (2021–2023) with projects having total cost estimates varying between $4.5 M/mile to $23.6 M/mile (INDOT's Next Level Roads Program, 2019).

5.2 Electrical Infrastructure Cost

The electrical infrastructure consists of the power distribution and charging systems. The cost breakdown and analysis proposed in this section is based on the design architecture presented in Section 4.1.1 for the charging system. The architecture is modular. A single module consists of four power transmitters (Tx) with the dimensions provided in Section 4.1.1. Based on the findings of the analysis in Section 4.1.2, it was found that two transmitters can be connected to a single inverter. This finding is used in the cost analysis, as shown in Figure 5.1. Each two inverters are connected to a single transformer-rectifier (TR) unit. As

TABLE 5.1
Typical precast panel costs

Cost Information for a Typical Panel per Square Yard (sy)	Estimated or Used by	Reference
$350	INDOT (for US 40, Richmond project)	INDOT
$350–$450	National Precast Concrete Association	Tayabji (2019)
$266–$319	AECOM	Zane et al. (n.d.)
$554	Louisiana DOT	Bucci et al. (2018)
$625	New Jersey DOT	Bucci et al. (2018)
$200	Texas DOT	Bucci et al. (2018)
$317	Utah DOT	Bucci et al. (2018)

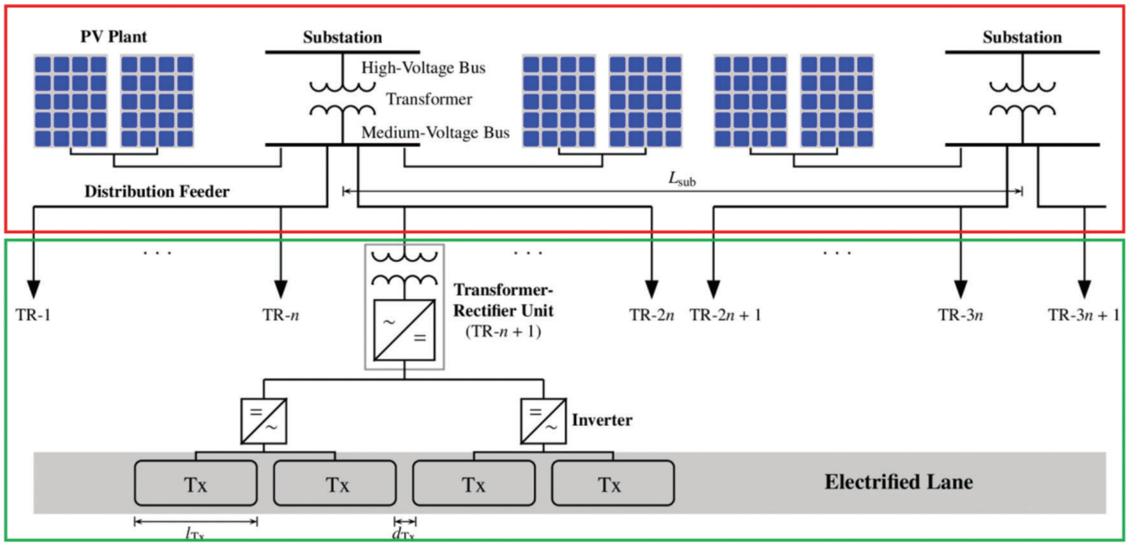

Figure 5.1 System layout for cost analysis (grid interconnection is shown in the red box, and the DWC system is shown in the green box).

mentioned in Section 4.1.1, the TR unit consists of a pad-mount low-voltage transformer and an active front-end rectifier. The components starting from the transmitters up until the TR units are referred to as the charging system components in this section. The interconnection to the grid is achieved through new distribution infrastructure that is designed specifically for the ER.

For every component of the system layout (Figure 5.1), unit costs were collected based on the literature (research studies or technical reports) and industry partners. The power transmitter is proposed to be an E-type core transmitter (Shin et al., 2014). Dimensions are specified in Section 4.1. The transmitter is made up of ferrite core segments of uniform thickness separated from each other by a fixed distance. The transmitter winding consists of a single turn of 2 AWG Litz wire going around the entire length of the transmitter. Based on these design details, a total cost of $12,000 is estimated per Tx.

In addition to the power transmitter, two power electronic devices are used in this architecture: the inverter and the active rectifier (in TR unit). An inverter drives one Tx at a time and is rated for 300 kW. The cost of the inverter is estimated as $0.09/Watt (Fu et al., 2018), based on its similarity to the solar inverter. Active front-end rectifiers are envisioned for this design. The rectifier supports two inverters and is therefore rated for 600 kW. The cost of each of these devices is estimated as $0.06/Watt (Fu et al., 2018). The TR unit also encompasses a pad-mount transformer rated for 620 kVA. The cost of this component is estimated to be $14,880 (Horowitz, 2019).

In this analysis, all new distribution infrastructure specific for DWC use is assumed. The grid interconnection costs include the cost of the distribution lines and the cost of the distribution substations. Overhead distribution is selected for the application as it is less expensive than the underground alternative. Each new substation is located at the midpoint of a road section and feeds two circuits, as shown in Figure 5.1. For cost estimation, the distribution lines of each road section covered by a single substation can be decomposed into two parts. The first part consists of a double circuit of conductors carried via wooden overhead poles from the substation to the road. The second part runs along the road section to the right and left of the substation. This part represents a single circuit of conductors carried on wooden poles. An estimate base cost per mile of $503,697 is found for the single-circuit distribution line, and $845,847 is calculated for the double-circuit line in Indiana (MISO, 2019). Added to the base cost is the cost of the AAC conductors and an overhead of 10% over the entire distribution line investment. The AAC conductor size is unique for each road section depending on the required traffic load. Cost estimates for different sizes of AAC conductors can be found in Wire and Cable Your Way (2020). It is assumed that the ER developer would bear the cost of distribution substations. A fixed base cost of $497,089 is estimated for every new substation construction, including the cost of land and site work. An incremental cost of $196,530/MVA (MISO, 2019) is added to the base cost based on each substation capacity.

It is evident by the unit cost estimation provided in this section, that cost is a function of power level, system design types, distance of coils from roadway surface, location, distance from substations and availability of distribution system capacity to support the DWC system load.

5.3 Financial Analysis (Case Study)

In this section, early adoption of the ER technology is analyzed for a case study on I-65. The portion of I-65 selected for the analysis is from Indianapolis to the southern border of the state of Indiana towards the state of Kentucky. A financial feasibility and risk assessment for the selected portion of I-65 is presented for both directions, northbound (NB) and southbound (SB). The competitiveness of the DWC solution as an alternative to conventional diesel vehicle technology is also assessed.

5.3.1 Data and Methods

The cost of the project considered is assumed to be financed through a loan structure. Assumptions and data used for the financial analysis are listed in Table 5.2.

The project construction is presumed to occur when there is no penetration of wirelessly charged EV technology for heavy-duty, medium-duty and light-duty vehicles (HDVs, MDVs and LDVs). In this analysis, the rate of market penetration for 30 years following the project construction is estimated based on the assumption of a logistic S-curve. S-curves are used to predict market penetration of new technologies (Konstantinou, 2019). Two levels of projected EV penetration are studied: medium and high. A final penetration level of 75% is assumed for trucks (HDVs and MDVs) and a lower level of 15% is assumed for LDVs for the high penetration case, while corresponding levels of 50% and 10% are assumed for the medium penetration case. The S-curve is modeled by Equation 5.1.

$$f_{pen}(t) = \frac{f_{pen,final}}{1+e^{-\alpha(t-T_0)}} \qquad \text{(Eq. 5.1)}$$

where t is the time in years, α is the growth factor and T_0 refers to the year at which half of the final level of penetration ($f_{pen,final}$) is reached. The proposed parameters for the analysis are α=0.45, and T_0=15 years. Figure 5.2 illustrates the electric truck (HDVs and MDVs) penetration growth per year for both penetration levels considered. In this analysis, it is assumed that all EVs, trucks and LDVs, travel on the right lane to use the DWC feature of the roadway.

Vehicle parameters are required for power consumption calculations. Mean vehicle parameters for an HDV (Haddad et al., 2019), MDV (Liao et al., 2019; Norouzi et al., 2016; Wang et al., 2016) and LDV (Knoop, 2019) are selected to represent all traffic that belongs to each of these three vehicle weight categories. Parameters include drag coefficient (C_d), rolling resistance coefficient (C_{rr}), frontal area (A), mass (m), auxiliary or hotel power (P_{aux}), additional charging power (P_{ch}) and drivetrain efficiency (η_{dr}). All parameters used in this analysis are listed in Table 5.3.

The design of the interconnection between the DWC system and the electric grid depends on the expected power requirement of the charging system based on the traffic load. In this analysis, the grid interconnection design is based on future projections of peak hourly traffic for expected final EV penetration levels on a high traffic day. The power requirements are calculated on a road segment-by-road segment basis considering the segment-specific traffic and grade.

The roadway is divided into 10- or 12-mile sections, depending on the penetration scenario, such that a single substation covers the entire section. An average distance of 0.25 miles between new substations and the roadway is assumed. Substation capacity and distribution feeder cable size are selected for each section via power flow analysis based on the traffic load requirement of the section. Table 5.4 lists the range of power levels for both cases for each direction of I-65.

TABLE 5.2
Financial analysis assumptions

Parameter	Value	CV/σ (%)[1,2]	Distribution[1]	Source
Traffic growth I-65 SB	0.76%	3.05 (σ)	Normal	Traffic data
Traffic growth I-65 NB	0.65%	2.72 (σ)	Normal	Traffic data
Annual Average Daily Traffic (AADT)	*	15	Normal	Traffic data
Final EV penetration	*	10	Normal	Assumption
Penetration midpoint year	15 years	10	Normal	Assumption
DWC system cost	*	20	Lognormal	
Real discount rate	7 %	5	Lognormal	Lawrence et al., 2015
Energy discount rate	4.64%	–	–	EIA, 2020; Lawrence et al., 2015
Loan interest rate	2.5%	10	Lognormal	Assumption
Loan period	30 years	10	Lognormal	Assumption
Annual operation and maintenance	1.5% of capital investment	5	Lognormal	Olsson, 2013
Project lifetime	40 years	–	Lognormal	Assumption
Electricity price[3]	6.6 cents/kWh	–	Lognormal	EIA, 2021

[1]Used for risk analysis only.

[2]CV: coefficient of variation, σ: standard deviation.

[3]This is the industrial electricity rate for Indiana in 2020. Electricity price projections for the rest of the project life follow the projections in (EIA, 2021) adjusted for Indiana.

*Depends on vehicle category and/or road segment and/or design.

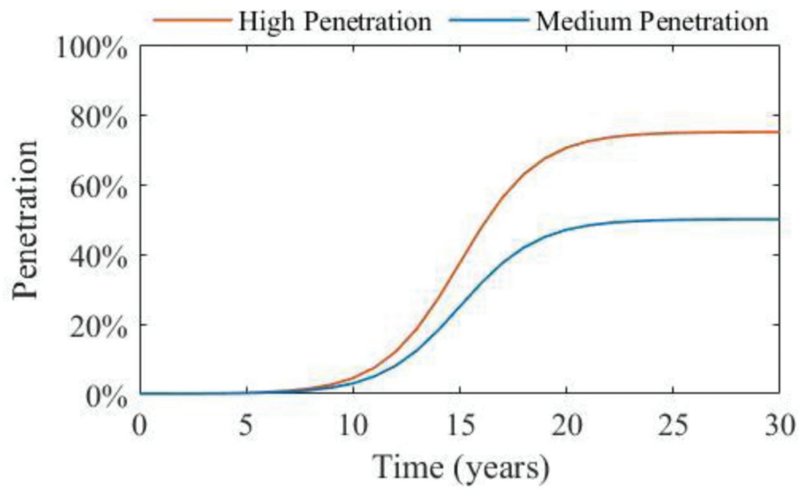

Figure 5.2 Penetration of wirelessly charged electric trucks throughout project lifetime for the high penetration and medium penetration cases.

TABLE 5.3
Vehicle parameters

Parameter	C_d	C_{rr}	A (m^2)	m (ton)	P_{aux} (kW)	P_{ch} (kW)	η_{dr}
HDV	0.65	0.0068	10.2	30.5	7.5	25	0.92
MDV	0.55	.0065	6.0	7.2	2.0	10	0.95
LDV	0.28	0.0060	2.4	1.5	2.0	2.5	0.95

TABLE 5.4
DWC system power requirements on I-65 S

Case Study	Selected Length of Road Section	Power Requirement at DWC System Input
High EV Penetration	10 miles	1.0–2.6 MW/mile for I-65 NB 1.3–3.6 MW/mile for I-65 SB
Medium EV Penetration	12 miles	0.7–1.6 MW/mile for I-65 NB 1.0–2.7 MW/mile for I-65 SB

Assuming that it is desirable to reduce the cost of deployment and minimize the disruption to the road network during construction, the installation of the ER technology can be combined with the implementation of planned resurfacing/reconstruction activities, such as a concrete overlay or pavement replacement. The costs for maintenance, repair, and rehabilitation activities (MR&R) of the pavement during the project lifetime are assumed to be covered by state taxes and federal funds (Dutzik et al., 2015; FHWA, 2020). Thus, only the annual maintenance of the electrical charging infrastructure is included in the feasibility analysis. A summary of the assumptions associated with the MR&R activities of the existing pavement and the ER is presented in Table 5.5.

5.3.2 Findings

5.3.2.1 DWC System Costs. A cost breakdown for implementing the DWC system on the described portion of I-65 for high and medium penetration scenarios is presented in Table 5.6. The full lane prefabricated construction method is selected for the reasons mentioned in Section 5.1. The study assumes that the entire I-65 S will be electrified using this construction method to ensure adequate power for HDVs. Additionally, based on the architecture and dimensions of the proposed design (Section 4.1), five out of every six concrete slabs along the ER constitute a single power transmitter (Tx), leaving one slab without any electrical components. In the case that the ER construction is scheduled with a MR&R activity, the civil infrastructure cost at the construction year (year 0) is found as the difference between ER construction costs minus the cost of the MR&R activity scheduled on the existing pavement the same year (at year 0), using the assumptions presented in Table 5.5.

5.3.2.2 Feasibility. One of the key factors in this analysis is the level of attraction of this technology to

TABLE 5.5
Assumptions for maintenance, repair, and rehabilitation (MR & R) activities

Year of Activity	MR & R Activity	Cost (sources)
ER construction		
Annually	Maintenance for electrical charging infrastructure	1.50% of initial cost (Olsson, 2013)
Existing concrete pavement		
Year 0	Option 1: Concrete overlay	$796,341/mile (Lamptey et al., 2005)
Year 0	Option 2: Pavement replacement	$1,711,874/mile (Lamptey et al., 2005)

TABLE 5.6
DWC system cost breakdown

	High EV Penetration ($/mile)	Medium EV Penetration ($/mile)
Charging system costs	2.23 M	2.23 M
Power distribution system costs	1.24 M	1.01 M
Civil infrastructure costs	3.08 M	3.08 M
Total[1]	*6.55 M*	*6.32 M*
Total differential cost for ER construction (MR & R option 1)[2]	5.76 M	5.53 M
Total differential cost for ER construction (MR & R option 2)[3]	4.84 M	4.61 M

[1]If ER construction is not scheduled with a major MR&R activity.
[2]Differential cost expressed as the ER total cost minus the cost of the concrete overlay activity scheduled on the existing pavement at year 0 ($796,341/mile).
[3]Differential cost expressed as the ER total cost minus the cost of a pavement replacement scheduled on the existing pavement at year 0 ($1,711,874/mile).

truck fleet owners/operators. The feasibility of the electrified roadway is largely dependent on the penetration level of EVs. Therefore, this technology should provide the driver of a conventional ICE vehicle with a reason to switch to an EV.

A break-even point analysis in terms of the cost of ownership, operation and maintenance of an electric truck versus the conventional truck is carried out to determine price attractiveness. Total ownership and driving costs are compared for the electric heavy-duty truck and its conventional alternative. The total costs consist of the ownership, operation and maintenance costs in addition to fuel cost (conventional or e-fuel). Sripad and Viswanathan (2018) specify the costs for both alternatives. Diesel prices for Indiana are used for the comparison. The initial price differential between the two alternatives is also considered, where the dynamic wireless power transfer retrofit charger cost (Den Boer et al., 2013) is added to the electric truck in addition to a battery with a 150-mi range (Sripad & Viswanathan, 2018). For the electric truck cost per mile to break even with the conventional vehicle, the energy cost per mile should balance the difference in costs. The energy cost per kWh is then calculated using the average speed and power demand at the roadway transmitter level assumptions presented in Section 4.1.1. The breakeven point for the electric truck is found to be 30.0 cents/kWh.

Using the assumptions presented in this chapter and a discounted cash flow, the attractiveness of the DWC project is assessed by comparing the levelized cost of the project in (cents/kWh) with the calculated breakeven point. The levelized cost of the project will determine if the project breaks even or is profitable. Feasibility is also assessed using three additional metrics: the net present value (NPV), the profitability index (PI) and the discounted payback period. The project is deemed feasible with a positive NPV, a PI ratio greater than 1 or a discounted payback period lower than the assumed project life. For assessment through these methods, the charging fee for using the DWC system is assumed to be equal to the breakeven point (30.0 cents/kWh).

Table 5.7 presents the results of the feasibility and attractiveness analysis. The resulting levelized costs indicate that both studied options can be deemed attractive for the DWC equipped-HDV owner against the conventional-HDV owner as they are both below the breakeven point. Attractiveness is enhanced with lower levelized cost. The case study of high EV penetration shows superior attractiveness. Based on the presented feasibility indicators, both case studies are considered feasible. Even though the system cost is higher, the case study targeted for high EV penetration demonstrates superior financial performance.

The integration of distributed roadside renewable energy generation is also considered. The natural synchronization of solar power levels and general traffic patterns is a consideration that makes this co-investment in ERs and PVs an intriguing possibility. Wind generation in the state of Indiana has great potential, owing in part to its flat terrain that allows for high wind speeds. Solar and wind power plants can be sized such that solar energy is mostly consumed on-site rather than exported to the grid. Renewables are assumed to be added by external investors at year 15 of project operation. A net-metering trading scheme would allow the ER operator to pay for all the energy generated by the renewables at the renewable energy compensation price. For electric energy coming from renewables, our analysis assumes a nominal purchase price of (5.0 cents/kWh) at the first year of the project. This price increases annually by 1.8%, following the average price increase of electricity tariff projections in (EIA, 2021). This price is higher than the average levelized cost of electricity (LCOE) for solar in the region for up to year 2040 (2.5–3.0 cents/kWh) and for wind (2.5–4.0 cents/kWh) (EIA, 2021). Table 5.8 presents the results of the feasibility and attractiveness analysis of the ER accompanied with different levels of distributed renewable energy integration. The first case presents a level of integration equal to the full hosting capacity of the distribution substations used for the ER power supply, whereas the second case considers 50% of the hosting capacity. It can be observed from the results, distributed renewable energy integration, not only provides the ER with cleaner electricity, but it also highly enhances its feasibility and attractiveness against conventional vehicles.

5.3.2.3 Risk and Sensitivity. Considering the volatility of multiple project assumptions due to market fluctuations, project risk is assessed via Monte Carlo simulation. Monte Carlo simulation estimates the values of feasibility indicators as functions of various uncertain investment risks, each expressed as a probability distribution. Following the feasibility analysis, the two EV penetration levels, medium and high, are assessed for risks.

Investment risk variables are identified as a first step. Probability distributions and levels of variability that are suitable for simulating the risk are then assigned. A normal distribution was selected for all traffic variables, while a lognormal distribution was selected for the financial variables. To evaluate the variability of investment risk variables, the coefficient of variation (CV) is used which is a standard normalized measure of dispersion of a probability distribution. The CV of the financial parameters and AADT followed the proposed values in Han et al. (2017). The standard deviation of the traffic growth on each direction was obtained from traffic data on I-65. All risk variables and corresponding distributions and CVs were presented in Table 5.2. MATLAB 2020a (MathWorks, 2019) was used for the Monte Carlo simulations.

The risk of the project is assessed at a charging fee equal to the breakeven point (30 cents/kWh). One thousand (1,000) Monte Carlo simulations were carried out for each EV penetration scenario (high and medium). The resulting relative frequency of occurrence of the simulations for the NPV are shown in Figure 5.3. The dotted black line indicates NPV of $0. Occurrence percentiles refer to the number of occurrences of a simulation outcome following certain criteria. The occurrence percentile of the NPV being less than 0 is referred to as the probability of financial failure of the project in this context. The distribution of the NPV values for the Monte Carlo simulations in addition to the probabilities of failure for both penetration levels studied are listed in Table 5.9. The high penetration case shows superior risk probability over the medium penetration case, which has an 85.7% probability to succeed. A medium EV penetration scenario might not be as attractive to investors as significant risk is associated with its implementation. In this work, several risk factors are involved. The failure probabilities would be reduced if the number and level of variance of risk factors are reduced.

The sensitivity of the NPV towards the input variables is also compared using Pearson's linear coefficient. For

TABLE 5.7
Feasibility and attractiveness analysis results

Parameter	High EV Penetration	Medium EV Penetration
DWC system cost[1]	$1,118.3 M	$1,066.7 M
NPV	$1,049.6 M	$464.7 M
Profitability index	1.94	1.44
Payback period	20.3 years	24.9 years
Levelized cost	*20.0 cents/kWh*	*23.3 cents/kWh*

[1]Length of ER on the outer lanes of I-65 NB and I-65 SB is approximately 231.3 miles.

TABLE 5.8
Feasibility and attractiveness analysis results with the integration of renewables

Parameter	High EV Penetration	Medium EV Penetration
Case I: Renewables covering 100% of substations hosting capacity (50% PV, 50% wind)		
NPV	$1,338.5 M	$654.4 M
Profitability index	2.20	1.61
Payback period	19.34 years	23.1 years
Levelized cost	17.2 cents/kWh	20.6 cents/kWh
Case II: Renewables covering 50% of substations hosting capacity (25% PV, 25% wind)		
NPV	$1,222.9 M	$576.0 M
Profitability index	2.09	1.54
Payback period	19.5 years	23.5 years
Levelized cost	18.3 cents/kWh	cents/kWh

TABLE 5.9
Risk analysis results for the NPV of the DWC project

	High EV Penetration (NPV)	Medium EV Penetration (NPV)
Distribution	Logistic	Logistic
Mean	$1,067.3 M	$487.8 M
Variance	$18.0 M	$85.0 M
Probability to fail	0.3%	8.3%

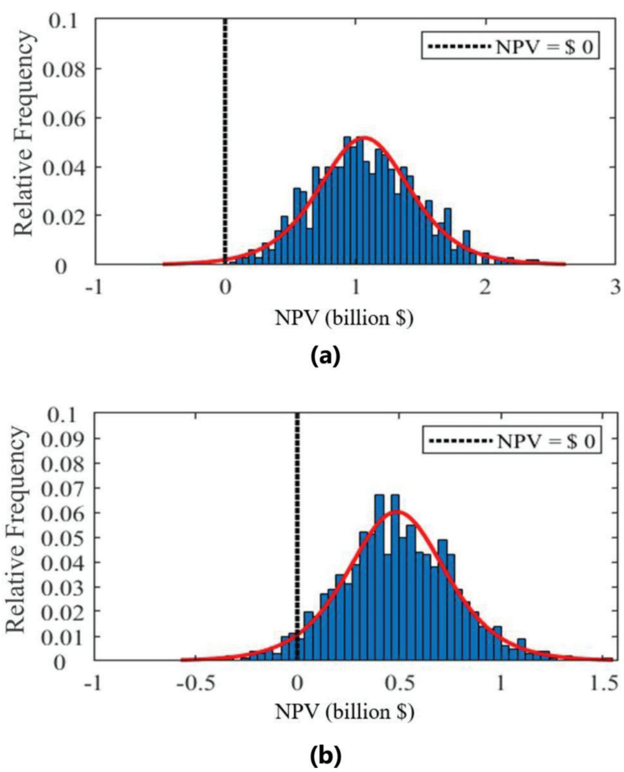

Figure 5.3 Risk analysis results-relative frequency of occurrence of NPV values for (a) high EV penetration and (b) medium EV penetration.

the high-penetration scenario, the real discount rate (-0.58) and the system cost (-0.48) showed the strongest correlation, followed by the time at which the penetration midpoint is reached (-0.47), HDV and MDV penetration levels (0.45). All other variables showed a coefficient lower than (0.1). For the medium penetration scenario, the capital cost showed the highest correlation (-0.58), followed by the penetration function parameters; the time at which half the penetration is reached (-0.47) and the final penetration level (0.47), the real discount rate (-0.45) and the electricity price (-0.06). In summary, the sensitivity analysis suggests that the final level of EV penetration and the time at which the penetration midpoint is reached are key influencing factors for the implementation of the technology. Capital cost and discount rate also highly affect the ER feasibility. Capital cost is a promising area of significant improvement at large-scale implementation of the technology.

6. CONCLUSIONS

6.1 Summary of Key Findings and Discussion

The objective of this project was to develop a practical framework for assessing the feasibility of electric roadway (ER) technology in Indiana and design a test bed for in-road electric vehicle (EV) charging technologies. This practical framework consisted of different tasks and sub-objectives. The specific objectives were the following:

- Conduct a literature review and gather lessons learned from best practices.
- Determine selection criteria and identify candidate locations of dynamic wireless charging (DWC) lanes based on a comprehensive list of demand-related, cost-related, EV-related, and other criteria.
- Design a flexible test bed using modeling and simulation techniques. This objective includes determining the overall architecture of the interconnection with the electric grid and exploring the architecture of the onboard pick-up and charging system.
- Assess the financial feasibility and risk of the technology.
- Offer recommendations to INDOT regarding the implementation of the technology.

6.1.1 Selection of Candidate Locations of In-Road Electric Vehicle Charging

To effectively implement the technology in Indiana and attract first adopters to the system, charging lanes need to be strategically deployed in the road network. Based on a comprehensive list of demand-related, cost-related, EV-related, and other criteria (Section 2.4.1), the results of the spatial GIS analysis showed that the most suitable locations for DWC lanes are on interstates that are characterized by high truck traffic, especially on I-70, I-65, I-465, I-90, and I-94, as well as near airports and ports and away from EV charging stations. Distance from intermodal facilities, military bases, planned construction/preservation projects, and floodplains did not significantly affect the identification of the most suitable segments. The suitability map also showed that the majority of the most suitable segments were found to be continuous or next to each other on specific interstates, indicating the potential for the construction of a system with longer ERs, not only potential test beds that may have the length of a single road segment. The interstates of Indiana are also part of the Alternative Fuel Corridor Program; the deployment of ER technology in Indiana would be more cost effective if the technology is a part of a larger system or if it is located at strategic places to attract federal funding to overcome the cost of research. Specific segments that stood out in terms of their suitability for locating ERs were presented in Table 3.3 of Chapter 3. I-Notably, I-70 and I-65 included more suitable and continuous segments compared to other roads of the network.

Based on the latter, a corridor level analysis was also conducted to investigate the power system availability of a candidate highway (I-65 corridor-from Indianapolis, IN toward Louisville, KY- or I-65 S) for which utility data were available. While this analysis determined that a relatively small portion of I-6 5 could be powered at 100% market penetration, the percentage of roadway powered rapidly increases as market penetration decreases. Additional capacity near I-65 S would be required to fully power the I-65 S corridor, but given a slow enough adoption rate, this additional capacity could be installed after construction of the technology hardware along the road as market penetration increases.

6.1.2 Development and Design of a Test Bed

After exploring the suitable locations for the technology, many challenges needed to be addressed in terms of the system design and charging control. A DWC power system that is capable of powering HDVs, assuming 100% penetration level and purely electric drivetrains, was designed for a suitable road segment in I-70. A layout of the distribution network was proposed. Multiple penetration levels of electrified trucks were considered for the analysis (25%–100%). The results reveal that aggregate power demand may fluctuate significantly, which can be detrimental to power system operation. For 100% penetration, an average load of 16.9 MW (2.2 MW/mi) is predicted. An average power consumption of 4.4 MW (0.6 MW/mi) is obtained for 25% penetration. Significant power ramp rates that can reach as high as $\pm$15 MW/s are also observed.

Models that enable the multi-objective design of the power conversion and wireless transmitter/receiver systems have been derived and used to perform an initial design of a charging system adequate to provide charge to HDVs operating at highway speeds. It was found that this appears technically feasible, in that adequate power can be transmitted across the relatively large airgap (26 cm) between the transmitter and receiver cores. However, to overcome the large airgap, the transmitter conductors and core will introduce loss (kW-level) into the pavement.

6.1.3 Localized Electric Road Construction Cost Estimation and Financial Analysis

Once the key components of the system have been modeled/designed, a cost analysis of the ER system was followed. The overall cost of an ER allows for a wide range of variation. This is because the cost is dependent on power level or target vehicles (light-duty vehicles/ LDVs versus HDVs), system design type, location, distance from substations and availability of distribution system capacity to support the ER load. Current prices of some materials such as copper and aluminum affect the costing as well.

Using I-65 as case study, it was found that DWC is economically feasible for the developer, and financially competitive for the EV owner at high and medium future projections of EV market penetration levels. The DWC system costs were estimated around \$6.3–6.6 M per lane-mile assuming a full lane prefabricated construction. If the construction of the ER is scheduled in conjunction with a pavement replacement activity, the respective DWC differential costs range between \$4.6 and 4.8 M per lane-mile. From an operator perspective, ER technology is competitive at a breakeven point of 30 cents/kWh. Payback periods for an early adoption deployment of the technology were found to range between 20 and 25 years. It is important to note that the feasibility and financial of the project are largely dependent on the penetration level of EVs adopting the DWC technology. The analysis presented in this report assumes medium and high penetration levels of trucks, as they are foreseen to be early adopters of this technology. Lower penetration levels result in lower usage of the system and may result in an infeasible project. Risk analysis unveiled high risks associated with lower projected EV penetration levels, while low risks were associated with a penetration level of 75% for medium and heavy-duty trucks within a 40-year project implementation period. The project's economic viability is also highly sensitive to the initial investment cost. This aspect can be improved with large scale deployment. Electricity prices paid by the ER developer to the electricity grid can also be considered a flexible area of improvement. This price can be negotiated in power purchase agreements with the utility operator. Distributed roadside renewables can be added to support the power consumption of the ER in-situ, which can reduce electricity costs.

Lastly, it is important to mention that the overall approach developed in this study for the assessment of the feasibility of the technology can be replicated by transportation planners or other stakeholders and used in other locations. Local considerations should be taken into account, but these can be easily incorporated in the general framework of tasks presented in this project.

6.2 Implementation Potential and Recommendations

Based on the work performed, the following primary recommendations for implementation are provided:

- The state level study conducted to identify the candidate locations for ERs provides a comprehensive list of all the necessary location criteria and can be a beneficial tool for transportation planners and decision makers who would like to establish effective and appropriate measures for designing and deploying the DWC system. The approach followed can help transportation panners and other stakeholders decide the most suitable locations of DWC lanes in any setting by examining the generated maps and then visiting the locations as a second step to ensure their appropriateness.

- Implementing the DWC technology jointly with major pavement preservation activities is recommended. Several pavement replacement activities are scheduled for the near future (2021–2023) for segments on I-70 that can be potential locations for an ER pilot. While the most suitable locations for the outright commercial operation of this technology are on interstates, a small testbed on a lower-class road project is needed to prove the technology in the field, under real environmental and traffic loads.
- To evaluate the ability of the existing power system to cover DWC along candidate locations, a substation selection algorithm was developed to evaluate roadway sections that can be powered under alternative power and penetration levels of EVs. Based upon studies applying the algorithm to several I-65 sections between Indianapolis, IN and Louisville, KY it was found that for HDVs, the existing substations are unlikely to serve future DWC needs. Thus, consideration should be given to the construction of new substations to support EVs as market penetration expands.
- The proposed layout of the power distribution network and the traffic data-driven design methodology for the charging system can be used as a guide to inform future DWC power system designs. The DWC system implemented on highways, especially if targeted for HDVs, requires a great amount of power. Aggregate power demand may fluctuate significantly. Transmission and distribution systems' available capacity and capability to accommodate the significant power fluctuations are important factors for consideration when planning a new implementation of the technology.
- A method of designing the integrated power converters, transmitters, and receivers for DWC has been developed and applied to consider charging of HDVs. It has been found that charging such vehicles at levels of 180 kW can be feasibly accomplished using existing transmitter/ receiver and power converters, pending validation of the models and the mechanical integrity of the pavements with the embedded transmitter. Model validation and pavement integrity could be readily performed using a small section (12×15 ft) of an ER test bed.
- The use of prefabricated slabs in the ER roadway pavement installation may be used for test beds at the early stages of implementation of the technology since it allows for trial and error during the slab fabrication process. In the future though, in-situ installation methods may be the choice to achieve economies of scale. A hybrid method that combines the use of precast panels and in-situ installation methods may also be considered to reduce construction costs.
- The level and growth of penetration of DWC equipped-EVs are among the top contributors to the project's success. Regulations and incentives that support the adoption of DWC equipped EVs (similar to ones for conventional EVs), particularly HDVs, would significantly improve this technology's competitiveness and feasibility. DWC system cost also has a great impact on its economics. Large scale deployment can significantly reduce the high initial investment.
- Investments in renewable energy resources (solar and wind) in the vicinity of ERs can reduce the electricity costs and associated greenhouse gas emissions. Renewable energy generation can be complemented with battery energy storage for addressing the intermittent nature of renewable energy generation and reducing impacts on the power grid.

6.3 Future Research Directions

Future research can work toward identifying additional criteria that might be important for locating DWC lanes and that are mainly used for local network analyses (e.g., terrain, vehicle capabilities, or the availability of space within the pavement). Furthermore, knowledge on the topic of DWC implementation is not adequate yet to allow hypotheses to be derived about the relative importance of the location criteria. Once the technology is more widely implemented, experts' opinions will be necessary to determine the weights of the criteria. Additionally, the analysis based on the substation algorithm can be expanded and include all the interstates in Indiana, as more data are obtained from the utilities.

Regarding the system design (power electronics and charging coils), future work needs to focus on the mechanical performance of pavement with embedded coils. Furthermore, it is likely that the overall charging system size (cost) and loss can be significantly reduced if the airgap between the transmitter coil (roadway) and receiver coil (vehicle) can be reduced. Quantifying the potential benefits is the subject of ongoing investigations. Additionally, the transmitter conductors and core will introduce loss (kW-level) into the pavement. The impact of this loss on pavement life will need to be considered. Finally, understanding the dynamics of the power converters within the power distribution network is necessary to provide confidence that voltage levels in the system are maintained during the rapid changes in power that will be observed in a roadway.

A follow-up research project is being planned with the goal to construct a quarter mile long test bed on a non-interstate in Indiana, considering the necessary location criteria for a successful testing and implementation of the technology. Such a project will help to develop construction techniques and provide a real-world testbed for optimizing the pavement/ dynamic wireless power transfer (DWPT) system. It will also be used to familiarize the stakeholders and surrounding communities with the technology and mitigate their concerns.

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APPENDICES

Appendix: Suitability Analysis

APPENDIX A. SUITABILITY ANALYSIS

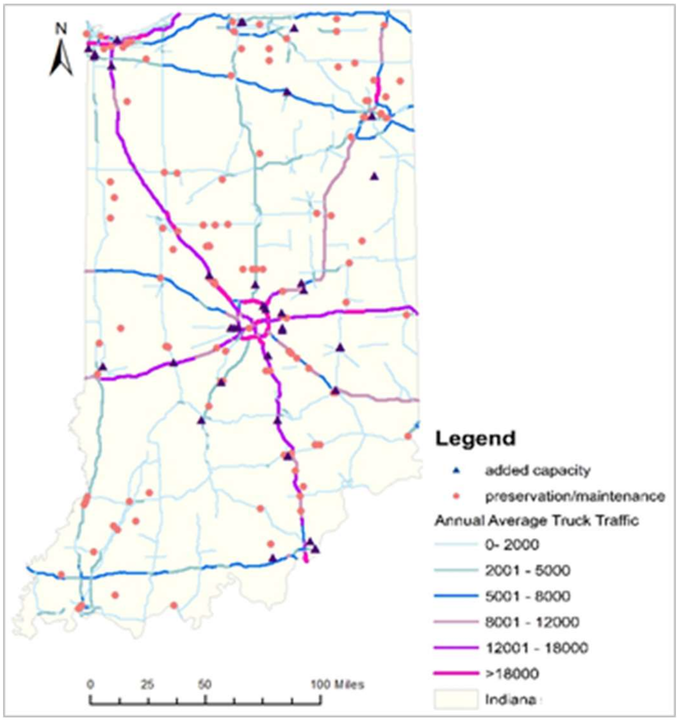

Figure A.1 Truck traffic and construction (added capacity)/preservation-maintenance projects.

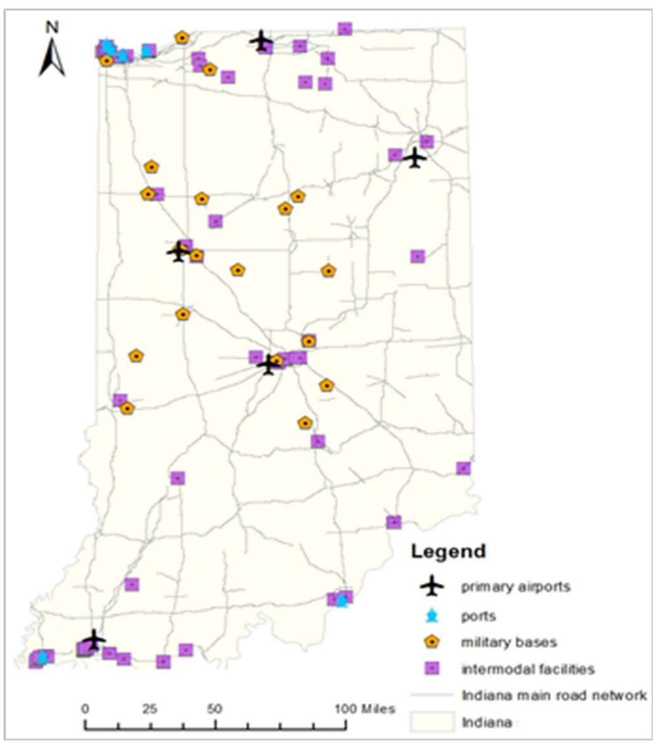

Figure A.2 Airports, ports, military bases and intermodal facilities.

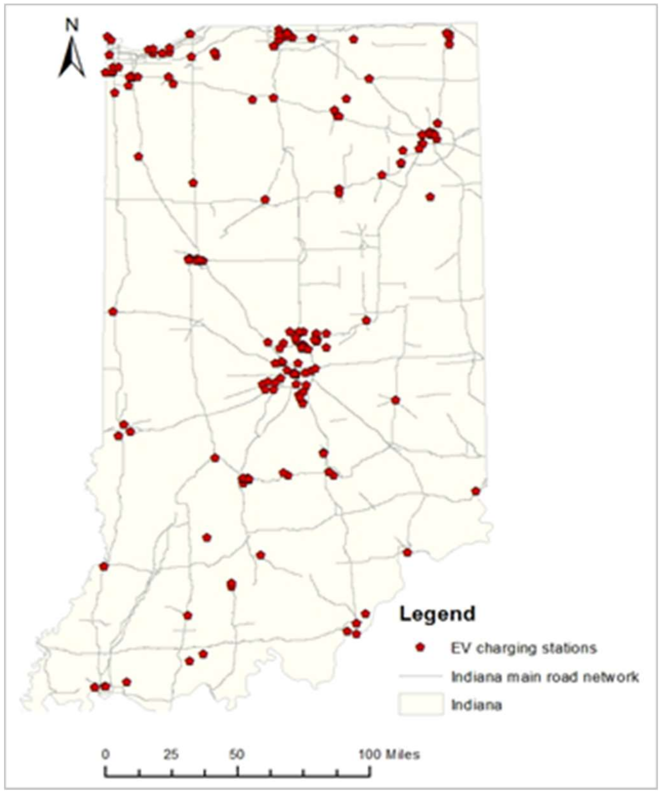

Figure A.3 EV charging stations.

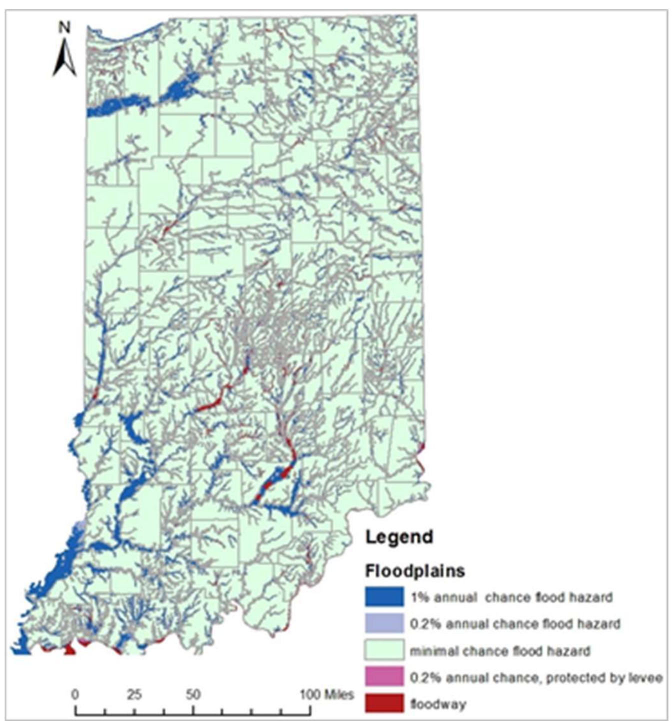

Figure A.4 Floodplains.

Table A.1 Data normalization-reclassification (1: highest suitability-5: lowest suitability)

Raster layer	**Normalized value/ Classified value**	**Classification method**	**Reference for classification**
Traffic network/truck traffic counts	1: >18,000 trucks 2: 12,001–18,000 trucks 3: 8,001–12,000 trucks 4: 5,001–8,000 trucks 5: 0–5,000 trucks	Natural breaks	Jenks (1967)
Distance from airports (primary airports)	1: ≤ 10 miles 2: ≤ 20 miles 3: ≤ 30 miles 4: ≤ 40 miles 5: ≤ Maximum value found	Manual	Measurements from Siemens project (Germany) (2017) and eRoadArlanda, (Sweden) (2018)
Distance from intermodal facilities	1: ≤ 5 miles 2: ≤ 10 miles 3: ≤ 15 miles 4: ≤ 20 miles 5: ≤ Maximum distance found	Manual	Assumptions (same distance as EV charging stations but with opposite direction from class 1 to 5)
Distance from military bases	1: ≤ 5 miles 2: ≤ 10 miles 3: ≤ 15 miles 4: ≤ 20 miles 5: ≤ Maximum distance found	Manual	Assumptions (same distance as EV charging stations but with opposite direction from class 1 to 5)
Distance from ports	1: ≤ 10 miles 2: ≤ 20 miles 3: ≤ 30 miles 4: ≤ 40 miles 5: ≤ Maximum value found	Manual	Assumptions (same distance as airports)
Distance from construction/maintenance activities	1: ≤ 0.001miles 2: ≤ 6.02 miles 3: ≤ 10.13miles 4: ≤ 14.79miles 5: ≤ Maximum distance found	Manual	Bateman et al. (2018) FABRIC (2014-b)
Distance from EV charging stations	1: ≤ Maximum distance found 2: ≤ 20 miles 3: ≤ 15 miles 4: ≤ 10 miles 5: ≤ 5 miles	Manual	FHWA (2018)
Floodplains	1: minimal chance of flood hazard 2: 0.2% annual chance of flood hazard, protected by levee 3: 0.2% annual chance of flood hazard 4: 1% annual chance flood hazard 5: floodway	Manual	Indiana Department of Natural Resources (2019)

Table A.2 Miles of top segments and similarity percentage to the base case for each sensitivity analysis scenario (*)

Criterion	Weight: 0.3		Weight: 0.5		Weight: 0.7	
	Miles	Percentage of similarity to base case	Miles	Percentage of similarity to base case	Miles	Percentage of similarity to base case
Truck traffic	1,122.03	85.35%	1,274.75	67.20%	1,339.71	65.19%
Airports	1,196.11	63.51%	1,479.06	54.36%	1,433.52	54.04%
Intermodal facilities	1,166.18	83.31%	1,249.81	70.61%	1,320.95	67.24%
Military bases	1,330.28	82.16%	1,410.61	77.14%	1,394.56	73.11%
Ports	1,289.03	69.33%	1,449.67	57.69%	1,450.67	41.81%
Construction projects	1,340.79	76.55%	1,268.83	76.09%	1,268.83	76.09%
Preservation projects	1,234.31	83.57%	1,160.49	74.67%	1,143.87	73.97%
EV charging stations	821.33	74.90%	962.14	7.89%	960.56	6.76%
Floodways	1,124.70	81.25%	1,096.23	79.88%	1,085.77	79.61%

(*) In order to compare the sensitivity analysis scenarios, the focus was based on the road segments that showed a suitability index of exactly one, that is the "top" segments. The total miles of the top road segments were recorded as a measure of the similarity across the scenarios with the base case. Additionally, the exact top segments that appeared both in the base case scenario and each of the sensitivity analysis cases were identified. This way, the percentage of similarity across the top road segments of the scenarios could be obtained and be considered as another measure of comparison across the scenarios.

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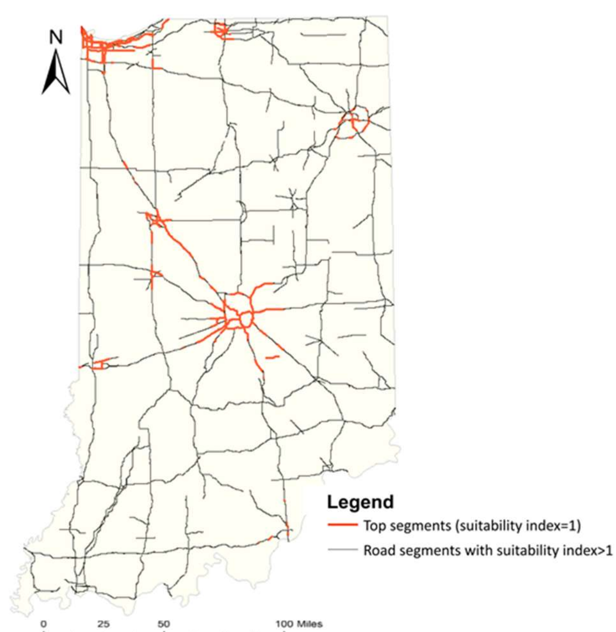

Figure A.5 Base case scenario (equal weights).

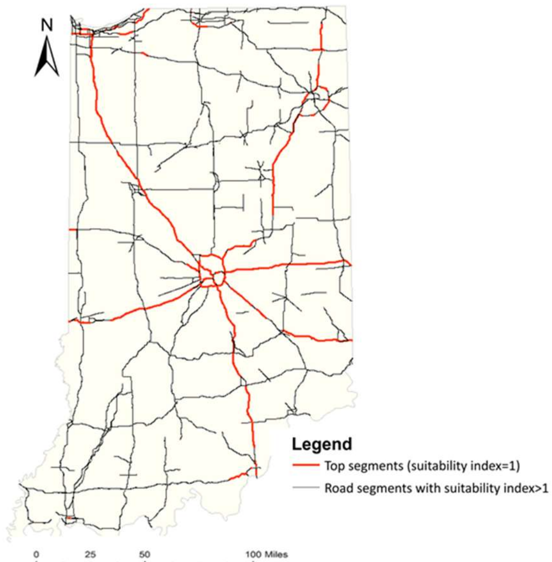

Figure A.6 Truck traffic (weight = 0.7).

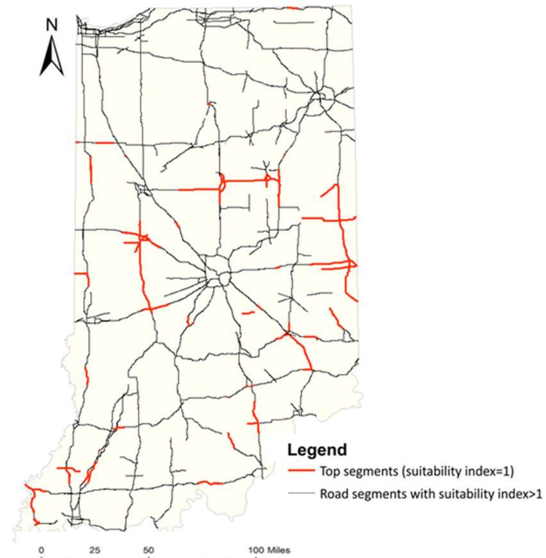

Figure A.7 Distance from EV charging stations (weight = 0.7).

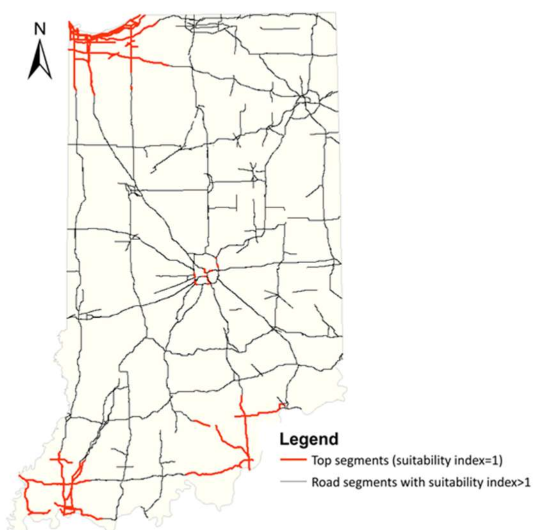

Figure A.8 Distance from airports (weight = 0.7).

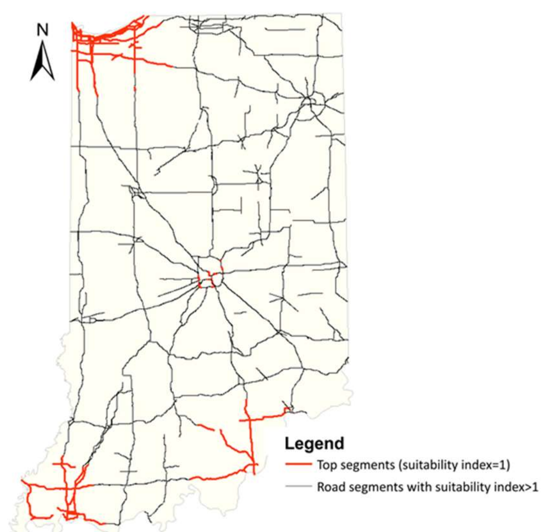

Figure A.9 Distance from ports (weight = 0.7).

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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