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Connected Vehicle Supported Electric Vehicle Charging Operations and Related Infrastructure Issues

Jennifer Johnson
Clemson University, jjohnson.clemson@gmail.com

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CONNECTED VEHICLE SUPPORTED ELECTRIC VEHICLE CHARGING OPERATIONS AND RELATED INFRASTRUCTURE ISSUES

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

by
Jennifer Ann Johnson
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Accepted by:
Dr. Mashrur A. Chowdhury, Committee Chair
Dr. Joachim Taiber
Dr. Jennifer H. Ogle
ABSTRACT

Due to the tremendous political, economic and environmental pressures the transportation sector is facing, the United States finds itself devoting more energy to innovative solutions like electric vehicle (EV) technologies. The first objective of this study was to analyze how utilizing real-time information dissemination transferring capabilities to vehicles, as envisioned in the “connected vehicle” system, could effectively facilitate the EV charging process at fast-charging stations. By simulating a traffic network of EVs in Matlab, it was found that the total time due to the battery charging process could be optimized for EVs that were able to use connected vehicle communications. Utilizing the optimization platform, the improvement of two vehicle parameters, extra travel time due to the charging and time spent in the charging station queue, as well as two charging station (CS) parameters, queue length and power output, were measured. The analysis revealed benefits at both a network and individual vehicle level. It was also found that load balance throughout the electric grid was also evenly distributed as EVs were routed to locations experiencing lower charging demand, resulting in minimized queue lengths and power outputs at each CS.

Traditionally, EVs are recharged at stationary sources, which results in significant time restrictions. Inductively coupled power transfer (ICPT) is a form of wireless power transfer technology that can alleviate EV user’s “range anxiety” while also minimizing the size and cost of the EV on-board energy storage system. As a result of ICPT charging, however, the cost will begin to shift from EVs to the infrastructure needed to charge them while in-motion. The problem now facing numerous agencies is that they will incur
significant costs constructing, maintaining, and operating ICPT infrastructure. *The second objective of this paper is to provide a thorough review on the costs associated with ICPT infrastructure and to present a business model that agencies can use as a shell for identifying and addressing the potential issues to cost-effective ICPT for EVs.* The successful implementation of charging station infrastructure will propel EV market penetration to the next level and bring our transportation system into the future.
DEDICATION

I dedicate this work to my parents, Jeffrey and Sandra Johnson, and to my brother, Arthur H. Johnson II. Without their encouragement, support, and love, I would not be the person I am today with such a bright future ahead of me. I love you all!
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CHAPTER ONE
INTRODUCTION

1.1 Problem Statement

Today’s society is becoming more and more energy dependent on steadily depleting petroleum resources. In fact, the transportation sector of the United States’ economy is the worst consumer of oil at well over half of the total amount of imported oil. Even worse, the vehicles that are consuming all of this petroleum exhibit the lowest energy efficiency rate of 20% (Tulpule et al., 2009). In efforts of diminishing the use of petroleum resources, major automobile companies are beginning to produce electric vehicles (EVs) on a commercial scale. Because of this increase in EV technology, a recent study claims that the US is expected to import 2.0-3.7 million barrels of oil per day less by 2030 due to this increase in the market penetration level of EVs. With this steady decrease in oil dependency, the United States will also experience numerous benefits in other areas such as decreased greenhouse gas emissions (Becker et al., 2009).

Although source of electricity, whether it is coming from a renewable or non-renewable source, may influence the total sustainability measure of EVs, these vehicles significantly contribute to a sustainable transportation community as they do not emit any pollutants to the environment. A shift towards EVs will transfer pollution generation from vehicles whose emissions are difficult to regulate, to power generation facilities that are regulated by federal agencies. Despite a number of current drawbacks with these
zero-emission vehicles, EVs are expected to significantly penetrate the market by year 2020 (Deloitte Consulting, 2010).

While EVs are a clear solution to our petroleum dependency and environmental problems, EV market penetration is severely hindered by not only incremental costs but also by difficulties in battery charging management. The EV drivers are unfamiliar with EV battery responsibilities like monitoring the state of charge (SOC) or locating one of only a few charging stations (CSs). This uncertainty in energy management for the driver has led to what is known as range anxiety. The availability of EV charging infrastructure is directly related to range anxiety and to the total time it takes for the EV to recharge (Boulanger et al., 2011). Because the EV industry is in its early stages, the supporting infrastructure is still in the deploying process, thus resulting in limited availability of CS infrastructure. Moreover, the corresponding infrastructure management, such as charging electricity network management, also remains in its infant stages.

One of the greatest factors affecting the market penetration of EVs is the inverse relationship of EV driving range and battery size. Because the battery pack is known to account for a significant percentage of the total vehicle cost, it is often restricted in size, thus also limiting the EV’s total driving range. Depending on market development, EV batteries can cost approximately $300k/WH to $650/kWh, which amounts to a total battery cost of $7,500-$16,250 for a small 25 kWh battery respectively. While a bigger battery may result in a longer driving range, it also significantly increases the cost of the EV (Lorico et al., 2011). In addition to cost, the battery itself contributes a large amount of weight to the vehicle, thus decreasing EV energy efficiency. By reducing battery size,
EV cost can be decreased while energy efficiency is increased. When dealing with EV-design, many engineers focus significantly on the design of the battery in efforts of reducing total EV costs. There are numerous variables that are taken into consideration in the design phase of EV batteries such as size, life, cost, and safety (DeVault, 2011). In addition to battery design, a major technical issue that should be addressed throughout the United States is in the design, construction, maintenance, and operation of the charging station infrastructure that EVs are so dependent upon. Ultimately, the goal of such infrastructure is to provide the EV with unlimited driving range while still minimizing battery size and vehicle costs. Charging station infrastructure will be supported more and more as EV market penetration begins to increase, thus supporting the design of more innovative charging schemes that will propel EV technology into the future.

Charging the battery for an electric vehicle must be safe, affordable, fast, and convenient. The travel distance of electric vehicles is heavily dependent upon the battery cycle and the location of the charging station. Although numerous charging stations have been built in recent years, the success of such vehicles will be decided by the ease of charging the depleted batteries (Sweet, 2010). Numerous studies have been completed that compare both the cost and time efficiency of varying charging schemes including: home, regenerative braking, solar, park-and-charge (PAC), battery swapping, and move-and-charge (MAC). Home charging is convenient because it is typically done during the evening hours with a light, onboard charger, but they are not capable of providing significant amounts charging current. These home chargers, or Level 1 chargers, typically cost about $1,350 to $1,500 to install and average about $3.00 to fully charge an EV in
the process of about 6-8 hours. These prices are highly dependent upon the proximity of
the utility service (Texas Transportation Institute, 2010). Regenerative charging and solar
charging are typically only used as charging enhancers to extend the driving range and
not to charge the battery as the sole source of power. The PAC method is typically done
at charging stations, which vary significantly by capacity and power. Level 2 PAC
systems can provide a full recharge in about 4-5 hours while a Level 3 PAC system, or
fast-charging station, can provide a 100-mile range charge in as little as 15 minutes.
Currently, these charging stations are installed by companies at a cost of about $2,000 to
$4,500 depending on the utility costs of the region in which they are installed. Another
alternative to addressing an EV’s limited range is a process known as “battery swapping.”
Companies like Better Place have created “battery swapping” stations where EV drivers
can swap out their depleted battery for a freshly charged battery without having to wait
through the charging process. This process, however, is hindered by the fact that EV
batteries are not standardized for varying vehicle models (Texas Transportation Institute,
2010).

A more recent charging scheme, MAC, provides the driver with the most
convenience as he/she is able to charge on the road by what is known as inductively
coupled power transfer (ICPT). The EV is essentially driving through the charging zone
because the ICPT system is actually constructed into the road itself. Inductively coupled
power transfer is a form of wireless power transfer technology that can alleviate electric
vehicle user’s “range anxiety” while also minimizing EV battery costs. In ICPT, power
sources are placed on the road and electric vehicles receive the power wirelessly while
moving on these sources at the average speed of roadway traffic. With this on-the-go charging scheme, the battery capacity and the discharge rate need not decide the maximum possible distance traveled. When charging an EV, it is important to ensure that the energy requirements of the EV can be sufficiently met by the power capabilities of the charging station infrastructure, but advanced infrastructure for charging schemes like ICPT might require significant capital and operating costs. Even more, ICPT requires guidance from connected vehicles since the ICPT charging process is more complicated than stationary charging and may be more difficult for drivers to handle.

Information technology will be transforming the transportation industry as vehicles and infrastructure are capable of communicating with one another through connected vehicle technologies and are sharing real-time data on important areas like current traffic conditions, weather, and road construction. In dealing with EVs, connected vehicle technologies will facilitate the industry as this constant flow of real-time communication between EVs and CSs will allow drivers to accurately and confidently locate the CS that will allow them to recharge their batteries in the shortest amount of time possible (Ezell, 2010). Such technology also allows the electricity industry to manage the potential charging demand from EVs.

1.2 Statement of Contribution and Potential Impact

Currently, the market penetration of EV technology is mainly limited by its battery and corresponding battery charging technologies. This paper explores a unique charging solution merging fast-charging and connected vehicle technologies for EVs.
This solution not only includes the most recent fast-charging technology but also innovatively introduces the up-to-date connected vehicle technology to manage the charging process, resulting in improvements of charging efficiency for both EVs and CSs. The “connected EV” charging framework presented in this paper demonstrates a path to the future surface transportation system that will facilitate accelerated market penetration of EVs by minimizing potential problems associated with fast-charging.

In the coming years, transportation engineers must be prepared to retrofit the current transportation infrastructure in order to account for the growing fleet of electric vehicles. The findings of this research can be incorporated into other models for further analysis, such as economic and environmental impact analyses, and can also be used to help decision makers develop better energy policies, specifically in funding for EV infrastructure projects that will be needed to propel EV market penetration to the next level. This type of research is essential in reducing US reliance on petroleum and greenhouse gas-producing fuels, thus creating a more sustainable mobility.

1.3 Objective of the Thesis

To reduce petroleum dependence and range anxiety, this paper presents an evaluation of the performance of connected EVs in efforts of monitoring the battery’s SOC and optimizing its battery charging process. The primary objective of this paper is to evaluate how connected vehicle technologies can facilitate EV fast-charging efforts at charging stations throughout the road network. This research will evaluate the efficacy of EV charging operations with and without connected vehicle technologies. The study will
aim to find an optimum charging process that satisfies both the capabilities of the connected vehicle technologies and the requirements of the electric vehicles. Connected vehicle technologies are a major transportation engineering application that allows vehicles to interact with roadside devices such as traffic controllers, traffic sensors, and other roadside agents. The benefits of integrating these communication technologies in EVs will be analyzed and evaluated in terms of not only total time needed for the charging process but also in regards to the impacts of varying market shares of EV integration on the electric grid itself.

Integration of the electric vehicle into the transportation sector will be predominantly controlled by the infrastructure that supports such technologies. With inductively coupled power transfer for electric vehicles, several infrastructure cost issues related to the construction, maintenance, and operation of such facilities need to be addressed. In addition, there must be a clear understanding on how such innovative infrastructure will effect coordination between the numerous public and private stakeholders involved, including departments of transportation (DOTs) and electric utility companies. The second objective of this paper is to analyze the costs associated with ICPT infrastructure and to present a business model that these agencies can use as a shell for identifying and addressing the potential issues to cost-effective ICPT for EVs. This paper will presents the costs associated with ICPT infrastructure and provide a potential solution to how this infrastructure can be constructed into the current transportation system.
1.4 Organization of the Thesis

Chapter 2 describes the background research and literature on capabilities of both connected vehicle and electric vehicle technologies as well as on the costs associated with ICPT infrastructure. Chapter 3 discusses the methodology undertaken to simulate the EV network in Matlab and the procedures taken to gather the current information for ICPT infrastructure. Chapter 4 provides a detailed performance evaluation of the simulation results, and Chapter 5 analyzes the collected ICPT cost data in order to develop an effective business model for funding the EV infrastructure. Chapter 6 concludes this thesis, offering conclusions and recommendations for further research.
CHAPTER TWO
LITERATURE REVIEW

The first two sections summarize studies related to electric vehicle operations, including both EV battery charging at fast-charging public charging stations and the capabilities of connected vehicle technologies implemented in the EV charging process. The final section provides a detailed overview of inductively coupled power transfer, explaining how this in-road charging system operates as well as the expected costs associated with such technologies.

2.1 EV Battery Charging at Fast DC Charging Stations

Electric vehicles are more energy efficient than internal combustion engines by utilizing a rechargeable battery to propel the automobile instead of other combustible fuels such as gasoline or diesel. Because EVs convert their energy from an electric motor, they have the potential in eliminating gasoline emissions when their power is derived from a clean electric energy supply, such as nuclear energy (Electric Drive Transportation Association, 2010). EVs store energy in a rechargeable battery that supplies the needed power to a motor controller. This motor controller facilitates the power supply to the electric drive motor as the EV driver accelerates/decelerates the EV. Rather than refueling at traditional gasoline stations, EVs must recharge their EV batteries by connecting to an outlet or charging device, also known as a charging station. While traditional CSs take several hours to recharge an EV battery, more recent
technology, known as fast-charging stations, can recharge the EV battery in as little as 15 minutes (Pacific Gas & Electric Company, 2011). This research will focus on optimizing the battery charging process by utilizing fast-charging stations.

When focusing on EV market penetration, driver behavior and charging station infrastructure availability will also play a major role in ensuring that EV technology is safe and efficient (DeVault, 2011). In order to achieve the greatest benefits possible from EV technology, there must be a sufficient amount of CS infrastructure available to support the EV charging process, which is the most common source of recharge for EVs. As the market penetration of EVs steadily increases, more attention is being focused on ensuring that the current CS infrastructure is adequately large enough to power such technology.

While most vehicle trips are less than 32 miles, as demonstrated by a 2005 National Personal Transportation Survey (NPTS), and can be supported by normal 120V home-charging stations, there is a growing need for CSs that can fully recharge EVs travelling on longer trips in a time efficient manner (Langer, 2005). Therefore, companies are beginning to develop and install fast-charging public charging stations that supply higher voltages and currents than home-charging stations and can thus recharge EVs quickly and conveniently.

The most recent codification for classifying levels of charging power was ratified on January 15, 2010, in the SAE J1772. AC Level 1 chargers, equivalent to home outlets, are on-board chargers that provide 120 VAC, 1-phase 12A rate with a 15 A circuit or 120 VAC, 1-phase 16 A rate with a 20 A circuit. These Level 1 chargers typically provide 4-6
miles of driving range for every hour of charging. AC Level 2 chargers are on-board chargers that provide 208 to 240 VAC, 1-phase up to and including 80 A, which provides 18-20 miles of driving range for every hour of charging. Both Level 1 and Level 2 chargers are intended to be used by drivers who can leave their vehicle at the charging location for an extended period of time. Therefore, this study does not take Level 1 or Level 2 chargers into consideration. A DC Level 3 charger, or fast DC charger, will be used in this analysis. DC Level 3 chargers are off-board chargers that can provide approximately 100 miles in as little as 15 minutes of charging (Boulanger et al., 2011). Currently, there are no international standards for Level 3 charging but revisions to SAE J1772 are expected to include fast charging standards by 2012 (Kissel, 2010).

The introduction and mass-scale deployment of EVs will require companies to invest in electrical charging stations. It is critical that electric utilities be able to predict the electricity demand because this will ultimately influence how efficiently the EV infrastructure will be able to operate. As EV market share increases, the demand for electricity will also increase. Because the electricity demand is dynamic, it is vital that the electric power generation and distribution utilities be able to foresee the peak times and locations of demand in order to maintain operation of the system and security of the electrical supply. In order to monitor and adapt to the dynamic traffic and electricity demands, smart charging methods can be employed to determine if the current supply of charging infrastructure is capable of meeting electricity demand of a specific penetration level of EVs (Waraich et al., 2009).
Various measures are being taken to offset the current drawbacks of EVs. In fact, this increase of EV usage in the transportation sector could decrease fossil fuel consumption by up to 20% (MacKay, 2009). This would ultimately make driving an EV more economically efficient than using a gasoline powered automobile (IEEE-USA, 2007). While charging station infrastructure may seem to be an issue for EVs, some studies claim that this could be an opportunity. In fact, EVs can also promote other sustainable ways of generating electric energy, including solar energy (Short et al., 2006). Another study predicted that EV technology will dramatically increase the cost effectiveness and efficiency of wind energy. This is predicted because EVs will primarily be charging at night, when wind power potential is greatest. The study also claims that the electric grid would not be over capacity because most of the EVs would be charging at residential stations throughout the evening hours. This type of charging means that the US’s infrastructure can actually accommodate 84% of the current internal combustion engine fleet if they were to turn into EVs (Fontaine, 2008). To successfully facilitate the transition from gasoline vehicles to EVs, there must be a conservative focus given to varying charging methods and technologies in order to support and accelerate the penetration of EVs into the transportation sector.

2.2 Capabilities of Connected Vehicle Systems

Ideally, all drivers desire a vehicle that will take them from point A to point B in the safest, quickest, and most economical way. In order to achieve this goal, engineers have begun integrating connected vehicle technologies into EVs in order to reduce...
greenhouse gas emissions using EV technologies and maximize energy efficiency using connected vehicle technologies. Connected vehicle technologies can be used to optimize efficiency by monitoring numerous variables including: driving behavior, battery SOC and cycle life history, and current traffic conditions. Drivers will be able to optimize each trip based not only on energy efficiency, but on time and cost as well. Essentially, the aim of connected vehicle technologies is to tackle some of the greatest challenges that hinder EV market penetration, including: realities of initial EV costs to the actual cost savings, effects of EV battery range and charging station availability on driver range anxiety, and impacts of the charging process on the electric grid (Boulanger et al., 2011).

As the transportation sector continues to see exponential growth on its highways, it is becoming clearly evident that connected vehicle technologies will be needed in order to monitor and resolve issues like traffic congestion and automobile accidents in real-time. Essentially, the ultimate goal of such innovative technologies is to take the human error out of driving and create an intelligent network of smart cars with constant communication with the surrounding infrastructure (Figueiredo et al., 2001). The benefits of ITS technology are numerous and provide benefits in areas of efficiency, safety, and cost. In fact, connected vehicle technologies have the potential to significantly reduce automobile accidents, total travel time, and the average stop time in traffic. Even more, ITS has an estimated 9:1 benefit-cost return in comparison to traditional highway investments with only a 2.7:1 return. It has even been predicted by the GAO that a national ITS program could reap benefits of up to $30.2 billion on only $1.2 billion in costs, which is a 25:1 return on investments. Additionally, ITS federal funding increases
of $2.5 to $3 billion annually could allow for an even faster EV market integration as more innovative ITS technologies will begin to be developed and generated for these alternative fuel vehicles (Ezell, 2010). This research will focus on one specific ITS technology known as connected vehicle technology, in which EVs will be able to communicate in real-time with the fast-charging infrastructure.

With conventional EV charging schemes, it is assumed that electricity prices are constant throughout the day, and as a result, EVs simply start charging whenever they are connected to a CS. Several studies have shown that such charging schemes, which do not rely on ITS technologies to monitor the charging process or on real-time charging schemes, result in both morning and evening peak demands (Karnama et al., 2010; Mets et al., 2010; Shao et al., 2010). When dealing with EV technologies, another study showed that ITS must be integrated into the charging process through smart charging in order to reduce these peak demands which are dynamic with respect to both time and location (Waraich et al., 2009). In such a charging scheme, there are several ITS technologies that allow grid-enabled vehicles, or connected vehicles, to interact with the electrical grid in real-time. There are numerous benefits of smart charging, including: real-time communication with utilities for monitoring the electrical grid loading, real-time pricing based on times of peak and off-peak demands, and charger load shaping to have optimal capture of renewable energy generation (Boulanger et al., 2011). Another study demonstrated that smart charging strategies are critical when trying to reduce peak demands and to actualize valley-filling in the load profile (Glanzer et al., 2011). In fact, more attention should be given to upgrading the existing power grids to smart grids,
rather than just creating more powerful grids, as the smart grids have the potential of streamlining the charging process, making it more energy efficient and cost effective.

By integrating intelligent energy management into EVs, the electric utility companies will also be able to improve their Supervisory Control and Data Acquisition (SCADA) system. Connected vehicle technologies have the potential of essentially transforming the current electrical grid into an intelligent network of constant communication between vehicles and infrastructure. In fact, this may eventually allow them to create a network in which the utilities can monitor and control both electrical equipment and demand in real-time. Even more, this will also allow the utilities to monitor the EVs while they are in motion, something they are not able to currently do because of privacy issues. This would also benefit EV drivers because the utility companies would be able to notify the EV of the nearest CS to charge at without having a negative impact on the grid. Therefore, regardless of EV fleet population, the electrical network would be able to withstand charging demand without causing an over capacity and blackouts because the utilities would be able to monitor and control the loads throughout the entire network in real-time (J.D. Fernandez et al., 2005).

In addition to optimizing the EV charging process through dynamic pricing and real-time electric grid balancing, connected vehicle technologies can also be implemented to provide the EVs with real-time traffic conditions. Because EVs have a limited driving range, it is critical that these vehicles do not get caught in an unforeseen traffic jam, leaving them incapable of reaching a CS in ample time. By using microscopic traffic simulation, one study demonstrated the benefits of a real-time traffic condition
assessment framework that uses vehicle-infrastructure integration (VII) with artificial intelligence (AI) algorithms to monitor the current conditions of the highway network (Ma et al., 2009). In such a system, these connected vehicles would be notified in real-time of any incidents that may have resulted in blocked lanes or traffic jams. For EVs, connected vehicle technologies such as these would enable the EVs to optimize total travel time to the CS while avoiding traffic jams in the network as well as total charging time by avoiding long queues at any specific CS. Without the smart grid, utilities would be forced to build additional power plants in order to support a high EV market penetration. Thus, by focusing on adding renewable power sources to the grid and by making the grid intelligent, a high EV penetration rate can be supported.

2.3 Overview of Inductively Coupled Power Transfer

The greatest obstacle for full market penetration of electric vehicles is due to their current limitations with the on-board energy storage system. Traditionally, EVs are recharged at stationary sources, which results in a significant amount of time loss at charging stations. As a first effort in reducing this time loss, a charging process known as fast-charging, or Level 3 DC charging, has been introduced by several companies. Fast-charging stations take approximately 15 minutes for a complete recharge for a 100-mile range EV and 45 minutes for a complete recharge for a 300-mile range EV. These fast-charging stations are essentially able to recharge several EVs in a similar way that internal combustion engine vehicles are currently refueled at gasoline stations (Boulanger et al., 2011).
A more innovative charging scheme now being considered, known as inductively coupled power transfer (ICPT), is able to charge an EV without having an actual physical connection between the power source and the load. Instead of plugging into a physical charging station, the EV is able to drive over a powered track where the charging unit automatically detects the EV and begins to charge the battery if needed, all of this while happening without the driver even realizing it (Covic et al., 2000). In Lommel, Belgium, Bombardier Transportation (2011) is in the process of developing an ICPT system using PRIMOVE Technology that provides unlimited power to both cars and buses by using a process known as induction, where an electric current flowing through a conductor, or ICPT transmitter, generates a magnetic field which then produces a current in a separate conductor, or EV power receiver, placed within the magnetic field. This ICPT system can eliminate the need for traditional plug-in charging stations. HaloIPT, a UK-based company, has actually developed a wireless charging system for EVs. This in-road charging system is able to charge the EV using electromagnetics for distances up to 15 inches, allowing for minor misalignment of the EV receiver pad and the charging system transmitter pad while the driver is traversing over the ICPT system (Cropley, 2010), as shown in Figure 2.1.
Recently, there have been many studies undertaken with the purpose of developing smart and efficient charging models. By using these technologies, motorists can charge their vehicles on-the-go, thereby eliminating the shortcomings of range and waiting times at charging stations. Lukic et. al. (2010) studied the use of an ICPT option, concluding that if the ICPT track has sufficient coverage, motorists could theoretically drive indefinitely, without waiting to charge their vehicles.

Other research is being conducted to evaluate the benefits of wireless charging technologies. In a recent study by Karalis et. al. (2008), the use of electromagnetic

Figure 2.1: In-Road Charging System for Electric Vehicles (Adapted from Cropley, 2010)
coupling was considered as a tool for energy transfer over mid-ranges. In another study by Imura et al. (2009), the experimental setup of wireless power transfer using helical antennas was studied. By using magnetic coupling for the energy transfer, they studied the effect of distance between the transmitting and the receiving antenna on the efficiency of energy transfer. Another study conducted by Lorico et al. (2011) demonstrated the use of ICPT to decrease average battery costs while maintaining EV range as well as to increase average EV range while maintaining a battery pack size of 28kWh for the average of three drive cycles, including federal urban driving schedule (FUDS), federal highway driving schedule (FHDS), and CU-ICAR neighborhood drive cycle. The battery pack costs savings were found to be approximately 20% and 39% and the vehicle driving range was found to increase by approximately 20% and 50% for the 20kW and 40kW ICPT rating cases respectively, as shown in Figure 2.2. The zero ICPT rating represented the base case scenario where ICPT was not used for EV charging (Lorico et al., 2011).
The greatest benefits of an ICPT system is that it essentially eliminates the energy storage shortcomings of EVs by allowing the vehicle to charge while driving through the network. The ultimate goal is to extend the EV driving range to distances of well over 300 miles while also significantly decreasing the size and cost of the EV battery. In fact, one study showed that an ICPT system can have positive effects on the vehicle range–to-cost relationship by allowing the battery size to be approximately 58% smaller while not sacrificing vehicle range. This study also determined that in urban settings with a UDDS driving cycle, only 1% of the driving cycle had to be covered by ICPT tracks in order for
the EV to acquire an unlimited driving range (Lorico et al., 2011). However, with this decrease in battery cost due to the installation of ICPT charging technology, it must be realized that the costs have now been significantly shifted from the EV itself to the innovative infrastructure needed to support them, and thus onto public transportation agencies.

2.4 Summary of Literature Review

Despite the research already completed in alternative fuel vehicles, there has been little done that focuses on the effects of connected vehicle technologies in EVs. This research will develop and evaluate a framework for applying connected vehicle technologies to facilitate the EV charging process, through simulation, in order to identify the overall advantages of implementing connected vehicle communication in EVs. The simulation for this study was completed using fast-charging public charging stations, which tend to be the preferred method of charging for long-distance trips. As the market penetration of EVs steadily increases, more CSs will be needed in order to ensure that the energy requirements of the EV can be sufficiently met by the power capabilities of the CS infrastructure while also not sacrificing the battery’s life or inconveniencing the driver. With the smart grid, utilities can monitor the network’s electrical load in real-time in order to ensure that the electric supply is meeting the current demand. Thus, by focusing on adding renewable power sources to the grid and by making the grid intelligent, an optimum EV penetration rate can be supported.
This paper aims to identify the benefits of connected vehicle technologies on EV charging operations by optimizing total travel time for the EV. The total travel time included the time needed to travel from the origin to the CS, the time needed to recharge at the CS, and finally, the time needed to travel from the CS to the destination node. As a result of this optimization, the improvement of two vehicle parameters, extra travel time due to the charging and time spent in the charging station queue, as well as two charging station parameters, queue length and power output, were measured. Specifically, attention is given to optimizing the total travel time of connected EVs and balancing the load of EVs at CSs throughout the entire network. The modeling results can be incorporated into other models for further analysis, such as utility companies monitoring the electric grid in real-time as well as economic and environmental impact analyses. These studies can also be used to help decision makers develop better energy policies, specifically in funding for EV ICPT infrastructure projects that will be needed to propel EV market penetration to the next level.
CHAPTER THREE

METHODOLOGY

3.1 Electric Vehicle Operations

This research focuses on connected vehicle technologies in EVs to help facilitate the battery charging process in efforts of reducing the total travel time of the EV drivers and thus optimizing the capacity of the current CS infrastructure as well. With connected vehicle technologies, drivers will be able to find the CS that will minimize the total time needed to complete an EV trip. Such optimization will reduce driver’s total travel time both in terms of total time travelling to the CS and time spent recharging at the CS itself. As a result of such optimization, the network of EVs will be balanced at each CS throughout the electric grid system. The simulation model was developed in MATLAB based on the simulation parameters summarized in Table 3.1, and the simulation results were used to evaluate the efficacy of implementing connected vehicle technologies in the EV charging process. The simulation was performed, and results for the connected EV scenarios were compared to a base case non-connected EV scenario.
Table 3.1: Simulation Parameters

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>Network Size</td>
<td>40x40, 35x35, 30x30 miles²</td>
</tr>
<tr>
<td>Distance between Nodes</td>
<td>1 mile [1.61 km]</td>
</tr>
<tr>
<td>Number of Vehicles</td>
<td>100, 300, 500, 700, 1000, 1500, 2000</td>
</tr>
<tr>
<td>Battery Capacity (Max SOC)</td>
<td>100 miles [161 km]</td>
</tr>
<tr>
<td>Initial Vehicle SOC</td>
<td>10 miles to 40 miles [32.2 km to 64.4 km]</td>
</tr>
<tr>
<td>Vehicle Speed</td>
<td>30 miles/hr [48.28 km/hr]</td>
</tr>
<tr>
<td>Constant Battery Drain</td>
<td>1 SOC = 1 mile [1.6 km] = 1 link traveled</td>
</tr>
<tr>
<td>Charging Station Type</td>
<td>Fast-Charging Public Charging Station</td>
</tr>
<tr>
<td>Charging Station Full Recharge Time</td>
<td>15 Minutes/100 miles [15 min/161 km]</td>
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</table>

The simulated vehicle network topology was built into a grid-like system with links 1 mile in length. Three network sizes were considered in this simulation, as listed in Table 3.1, and the 40x40 miles² network with 1,600 nodes has been shown in Figure 3.1. In addition, there were EV charging stations located 5 miles apart. The CSs formed a balanced grid throughout the network with locations at every fifth node in both the rows and columns and with no CS located on an actual network boundary. Therefore, there were 49 CSs for the 40x40 network, 36 CSs for the 35x35 network, and 25 CSs for the 30x30 network. The study simulated the presence of electric vehicles at varying amounts of EV penetration, including: 100, 300, 500, 700, 1000, 1500 and 2000 EVs, in order to analyze the impacts connected vehicle technologies would have on the network as the number of EVs continued to increase. Each vehicle was represented by a node traveling at a speed of 30 mph so that the vehicle would traverse each 1-mile link during every time step, which was set at two minutes. For both the connected and non-connected scenarios, each EV randomly selected a boundary node as an initial starting location and traversed the network to its destination node on the opposite boundary. For example, the
EV would travel from node (40,17) to (0,37) or (26, 0) to (33,40) as shown in the 40x40 network in Figure 3.1. The exact starting and ending points on the boundary were randomly assigned. The vehicles stopped only at nodes, not on links, where the SOC for each EV would then be updated.

![Simulated Vehicle Network Topology for 40x40 Grid Size Scenario](image)

**Key:**
- **Red Circle**: Charging Station
- **Small Black Dot**: Network Node
- **Green Triangle**: EV Node
- **Blue Line**: Road Link

*Figure 3.1: Simulated Vehicle Network Topology for 40x40 Grid Size Scenario*
The battery capacity, or maximum SOC, for the EV was assumed to be 100 miles, and each EV was randomly assigned an initial vehicle SOC that would require it to have to charge at some point during the simulation process as the optimization of the actual charging process was of primary concern. Therefore, the initial SOC was 20 to 40 miles for the 40x40 network, 15 to 35 miles for the 35x35 network, and 10 to 30 miles for the 30x30 network. In addition, each EV maintained an additional 5-mile cushion in the SOC to ensure that the battery was not completely depleted while traveling to its final destination, thus reducing and controlling driver’s range anxiety. In both the connected case and the non-connected case, the EV was required to find a CS if its SOC was less than the total remaining travel length plus an additional 5 mile cushion. Once at the CS, the EV’s battery was charged to a SOC that would allow it to reach its destination with 5 miles extra SOC left; it was not recharged to a fully charged state. It was assumed that full recharge on the fast-charge public charging stations takes approximately 15 minutes for a 100 mile range EV, which was determined to be 6.67 SOC (miles)/minute (Morrow et al., 2008). With these fast-charging CSs, the EV would receive enough energy to travel an additional 6.67 miles for every minute it was recharging at the fast-charging CS; the EV battery would thus be fully recharged in 15 minutes with a range of 100 miles. Thus, the charging process would be on the scale of only minutes instead of hours.

The simulation considered four different scenarios when integrating connected vehicle communications into the EV charging process. Case 0, or the base case, considered only non-connected EVs in the network. In this case, the EVs would traverse the network as shown in Figure 3.1 with Global Positioning System (GPS) technologies
only. In other words, the non-connected EVs would travel to CSs that were closest in distance. In contrast, Case 1, Case 2, and Case 3 each simulated networks in which EVs would use connected vehicle technologies to travel to the CS in Figure 3.1 that would minimize total time; the EV would travel to the CS that would have the lowest travel time as determined by Equation 1. For each EV in Case 1, the process of assigning the CS was run only one time when the EV first entered the simulated network, and the estimated wait time at the CS was recognized as the current wait time. In Case 2, the criteria of assigning the CS and determining the estimated wait time at the CS were the same as Case 1, but the difference was that the optimal CS assignment for each EV was updated at every time step, or every two minutes. Therefore, Case 2 used real-time CS assignment in order to optimize the CS process while considering dynamic changes that may have occurred in the network while the EV was in route to the assigned CS. Case 3 also used real-time CS assignment at each two minute time step as in Case 2, but in Case 3, the estimated wait time as used in Equation 1 was determined by predicting the wait time for when the EV would actually arrive at the CS. In detail, each CS had a demand queue and an actual queue. With these queues, the number of EVs in the CS and the time demand needed to charge each EV at the time when the vehicle actually reached the CS could be determined via connected vehicle technologies and could thus notify the target EV of the estimated wait time at each CS.

For this simulation, the key module was the “assign CS,” and two algorithms were used in performing the test. For the base case, which is the non-connected scenario, the EV was assigned to the nearest CS using GPS technologies regardless of queue length
or wait time. For the connected cases, the EV was assigned to the CS with the smallest total travel time using connected vehicle technologies, as defined in Equation 1:

\[
\text{Total Travel Time} = \text{time from current location to CS} + \text{time in CS} + \text{time from CS to destination}
\]
\[
\text{where time in CS} = \text{estimated wait time of CS} + \text{charging time}
\]

Equation (1)

The vehicle model for the simulation has been represented in Figure 3.2. In this flow chart, a status of zero represents normal driving conditions in which the SOC is high enough to provide enough power for the EV to reach the final destination as well as provide a 5-mile cushion. A status of one signifies that the EV has reached a SOC in which a CS is needed to be assigned, and a status of two signifies that the EV has begun moving towards its assigned CS to begin the recharging process. In this stage, the “Update CS k” function only applies to Case 2 and Case 3 (as represented by the dotted line in Figure 3.2), in which the EV is assigned to the most optimal CS at every time step. A status equal to three shows that the EV is currently waiting in a queue at the fast-charging station, and a status equal to four means that the EV is in the actual process of recharging its own battery. In this study, the benefits of connected vehicle technologies are measured by analyzing how connected EV networks can reduce the extra time needed for EV drivers to recharge at CSs as well as balance the distribution of EVs that are charging throughout the network.
Figure 3.2: Simulation Vehicle Model Based on Electric Vehicle State of Charge
3.2 ICPT Infrastructure Cost Issues

As EV battery size continues to decrease, the cost will begin to shift from the electric vehicle to the complex infrastructure needed to charge such vehicles while in-motion. The problem now facing numerous agencies, specifically the state DOTs and electric utility companies, is that under such a charging paradigm, they will have to invest significant costs constructing, maintaining, and operating EV charging infrastructure. One of the most significant problems is determining whether stationary fast charging is more cost effective than dynamic charging.

This section aims to assign costs for each element in the inductively coupled power transfer (ICPT) system so that the stakeholders involved can be aware and prepared to handle all of the cost issues. ICPT cost data was collected by seeking expert insight from professionals at Oak Ridge National Laboratory and Clemson University International Center for Automotive Research (CU-ICAR). In addition, recent statistics and data were verified through the Electric Power Research Institute (EPRI) that conducts research directly related to the generation, delivery, and use of electricity for the benefit of the public. EPRI consists of scientists and engineers who are experts in both academia and industry whose common goal is to solve issues related to electricity, including reliability, efficiency, safety, and the environment, as well as to provide innovative technologies, policies, and economic analyses to support research in emerging technologies.

According to EPRI, an ICPT system, or what they refer to as an integrated energy storage system, consists of three major components: energy storage system (ESS), power
conversion system (PCS), and balance of plant (BOP). This section of the paper will give an in-depth analysis of the major costs incurred due to installing ICPT infrastructure for EVs including capital, maintenance, and operations. As agencies begin investing in such infrastructure, they must be cautious in estimating the costs of ICPT infrastructure as history has proven that the costs associated with PCS and ESS systems are heavily underestimated. In addition, it must also be taken into consideration that transferring large amounts of energy requires suitable battery chemistries, which can also be very costly (Gyuk, 2003).
CHAPTER FOUR
PERFORMANCE EVALUATION

This section presents the benefits of connected vehicles to facilitate charging operations in EVs. Throughout this study, it was found that battery charging optimization occurred for EVs that were able to use connected vehicle technologies to directly receive information regarding current CS availability and wait times at actual CS locations. The analysis was performed for the optimization of total travel time for the EV to travel from origin to destination and with the added time due to charging. As a result of this optimization, the improvement of two vehicle parameters, extra travel time due to the charging and time spent in the CS queue, as well as two CS parameters, queue length and power output, were measured.

4.1 Optimization of Vehicle Parameters

Without connected vehicle technologies, drivers may be less efficient in the charging process because they may select a CS based only on nearest location without considering other important information such as queue length or wait time at the charging station itself. Connected vehicle communication would allow the EV to directly receive information regarding the current conditions at each CS, and thus, the driver would be able to select the CS that would minimize the total extra time due to charging. The extra time due to charging was defined as the difference between the total time in the case where recharge was needed to complete the trip and the case where recharge was not
needed. This metric was essentially a combination of the parameters of distance traveled, wait time in the CS queue, and time spent charging to the needed SOC to reach the destination with 5 miles of SOC remaining. By analyzing this metric, the total time associated with the complete recharging process for both a connected and non-connected EV could be compared, as shown in Figure 4.1 and Table 4.1.

Figure 4.1 displays the extra time due to charging for each scenario of varying EV penetration level in each of the network sizes. The distance between marks also represents one standard error for each case. It was found that the effects of connected vehicle technologies on the battery charging process become more evident as the level of connected vehicle communication increased. In other words, Case 1 resulted in a lower
extra time due to charging and smaller standard error than the base case; Case 2 and Case 3 further improved on these benefits. It was also found that the benefits of both Case 2 and Case 3 were similar for most simulation scenarios. While it was expected that Case 3 would improve on the time savings from Case 2, it must be noted that there were not significant savings for Case 3. This is due to the fact that EVs in both the demand queue and actual queue only considered EVs that were actually in the simulation network while calculating the real-time estimation of wait time at the CS for when the vehicle would arrive at the CS. In other words, the EVs that would enter the simulation network between the time the CS was assigned and the time the EV actually arrived at the CS were not considered in determining the estimated wait time. Therefore, it was determined that the major reason as to why the performance of Case 3 was not significantly better than Case 2 was because Case 3 could not include the EVs that would enter the network in future time steps in the estimation of wait time. As a result, the inaccuracy from this fact was large enough to impact the performance of algorithm 3 (Case 3).

Based on the number of vehicles at a CS, the wait time for a recharge in the CS queue might reach unacceptable levels for the driver. If a driver selects a CS location based solely on closest distance, there is a good probability that the driver will be severely inconvenienced by an unexpected, long queue at the CS. By integrating the use of roadside controller communication with the EV, the CS with the optimum wait time can be selected, which guarantees that the driver will face the least amount of time to fully recharge the EV. This expectation is supported by the results presented in Figure 4.2 and Table 4.1 for each of the four simulation cases.
Figure 4.2: Average Time Spent in Charging Station Queue

Figure 4.2 displays the average time spent in the CS queue as well as the standard deviation for each scenario of varying EV penetration level in each of the network sizes. It was found once again that the effects of connected vehicle technologies on the battery charging process improve the mean and standard error for Cases 1, 2, and 3 in most of the simulation scenarios. The standard error was shown here in order to highlight the fact that the improvements are not only on the network level but also on an individual vehicle level. In other words, most of the EVs are benefiting from connected vehicle communication technologies. Case 2 and Case 3 were capable of once again improving both the mean and standard error over Case 1 because the EVs are assigned to a CS in real-time while taking into consideration the dynamic changes throughout the network during the entire simulation process.
Table 4.1: Evaluating the Driver Benefits of Connected EVs in the Charging Process

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In Table 4.1, it was found that Case 1 simulation results outputted negative numbers, or performance degrades, because of the fact that the CS assignment was not capable of changing throughout the simulation. The algorithm used for Case 1 was not capable of changing the CS assignment to account for new vehicles that would be constantly entering the network at every time step. Case 2 and Case 3, however, were
able to dynamically re-assign CS to each individual EV at every time step, thus optimizing the total time for charging in real-time. This was shown in Table 4.1 by the fact that Case 2 and Case 3 had no performance degrades for any of the simulation scenarios; connected vehicle communication technologies were able to efficiently optimize the CS process in real-time.

In addition, it is determined that the total travel time metric could be combined with results of traffic congestion monitoring at the roadside controller in choosing the most time efficient route. In other words, connected EVs would be able to detect traffic congestion and avoid these routes in choosing a CS location, thus reducing total travel time even more. The resulting chosen CS could then help alleviate the problem of range anxiety by ensuring that the EV always reaches the CS before its battery was completely depleted.

4.2 Optimization of Charging Station Parameters

The parameters used to evaluate the benefits that connected vehicle technologies used throughout the EV charging process provide to the CS network itself are the queue length and power output, as shown in Table 4.2 and Table 4.3 respectively. It was shown that connected EV networks were able to greatly reduce the average queue length and average power output for most of the simulation scenarios.
Table 4.2: Average Charging Station Queue Length

<table>
<thead>
<tr>
<th>Number of EVs</th>
<th>Grid Size</th>
<th>30x30</th>
<th>35x35</th>
<th>40x40</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>100</td>
<td>Mean</td>
<td>0.48</td>
<td>0.48</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>1.16</td>
<td>0.96</td>
<td>0.58</td>
</tr>
<tr>
<td>300</td>
<td>Mean</td>
<td>1.08</td>
<td>1.08</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>1.82</td>
<td>0.81</td>
<td>0.61</td>
</tr>
<tr>
<td>500</td>
<td>Mean</td>
<td>1.52</td>
<td>1.56</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>2.26</td>
<td>1.12</td>
<td>0.87</td>
</tr>
<tr>
<td>700</td>
<td>Mean</td>
<td>1.68</td>
<td>1.52</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>2.56</td>
<td>0.82</td>
<td>0.56</td>
</tr>
<tr>
<td>1000</td>
<td>Mean</td>
<td>1.68</td>
<td>2.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>2.56</td>
<td>0.96</td>
<td>0.5</td>
</tr>
<tr>
<td>1500</td>
<td>Mean</td>
<td>1.84</td>
<td>2</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>2.54</td>
<td>0.65</td>
<td>0.58</td>
</tr>
<tr>
<td>2000</td>
<td>Mean</td>
<td>1.88</td>
<td>2.56</td>
<td>1.4</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>2.54</td>
<td>1.08</td>
<td>0.58</td>
</tr>
</tbody>
</table>
Table 4.3: Average Power Output for Charging Station

<table>
<thead>
<tr>
<th>Number of EVs</th>
<th>Grid Size</th>
<th>30x30</th>
<th>35x35</th>
<th>40x40</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Case</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>100</td>
<td>Mean</td>
<td>124</td>
<td>121</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>144</td>
<td>65</td>
<td>64</td>
</tr>
<tr>
<td>300</td>
<td>Mean</td>
<td>365</td>
<td>359</td>
<td>361</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>407</td>
<td>142</td>
<td>95</td>
</tr>
<tr>
<td>500</td>
<td>Mean</td>
<td>617</td>
<td>599</td>
<td>599</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>664</td>
<td>214</td>
<td>217</td>
</tr>
<tr>
<td>700</td>
<td>Mean</td>
<td>856</td>
<td>835</td>
<td>835</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>943</td>
<td>282</td>
<td>225</td>
</tr>
<tr>
<td>1000</td>
<td>Mean</td>
<td>1216</td>
<td>1184</td>
<td>1186</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>1335</td>
<td>343</td>
<td>294</td>
</tr>
<tr>
<td>1500</td>
<td>Mean</td>
<td>1828</td>
<td>1784</td>
<td>1789</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>1995</td>
<td>484</td>
<td>356</td>
</tr>
<tr>
<td>2000</td>
<td>Mean</td>
<td>2442</td>
<td>2382</td>
<td>2384</td>
</tr>
<tr>
<td></td>
<td>Std. Error</td>
<td>2679</td>
<td>539</td>
<td>471</td>
</tr>
</tbody>
</table>
More importantly, connected vehicle technologies would also help the utilities load balance the electric grid since connected EVs would be routed to locations experiencing lower electricity demand, which are essentially the CSs with the smallest queue lengths. This in turns helps the utility companies avoid failure of a portion of the electric grid due to excessive demand resulting in the failure of the associated transformer. In the simulation, all EV trips started from one boundary and were set to travel across the entire grid to the opposite network boundary. The EV required a battery SOC that would allow it to travel to its destination plus an additional 5-mile cushion in order to reduce range anxiety.

For the base case scenario, the EV would thus find the closest CS once its SOC fell below the required state, which was typically at the boundaries at the start of the vehicle’s trip since the EV began with an limited, initial SOC range. For Case 1, Case 2 and Case 3, however, the connected EVs could be evenly distributed throughout the network as the connected vehicles could be routed to a CS with the shortest queue length, or smallest demand. As a result, the power output throughout the network would also be evenly distributed, not resulting in power overloads at the stations located near the network boundary. These distributions are highlighted in Figure 4.3 for the 30x30 network containing 25 CSs and with an EV penetration level of 2,000 vehicles.

It was found that Case 1 was able to improve over the base case by assigning EVs a CS with lowest demand in order to minimize queue length and power output across the grid. Case 2 and Case 3 improved on these parameters even more by updating EVs to a CS in real-time by taking into account the CS network conditions at every time step. As
mentioned before, Case 3 provided approximately the same amount of time savings as Case 2 due to the fact that it only considered EVs in the simulation network when predicting the estimated wait time for the targeted EV when it reached the CS at a later time step in the simulation.
Figure 4.3: Evaluating the Network Benefits of Connected EVs in the Charging Process
CHAPTER FIVE
COST ANALYSIS

This section presents the cost analysis for determining whether dynamic charging is more cost effective than stationary fast charging. As EV battery size continues to decrease, the cost will begin to shift from electric vehicles to the complex infrastructure needed to charge such vehicles while in-motion. The problem now facing numerous agencies, specifically the state DOTs and electric utility companies, is that under such a charging paradigm, they will have to invest significant costs constructing, maintaining, and operating EV charging infrastructure. This section provides the estimated costs from installation to maintenance and operations as well as a proposed business model in which to fund such large-scale, innovative projects.

5.1 Capital Cost Issues Associated with ICPT Infrastructure Construction

Currently, ICPT infrastructure is ideal only in a research lab setting because it is very expensive to install on a commercial scale. The current estimate of the construction and commissioning of ICPT infrastructure is at $1.1 M/lane mile, which amounts to $700,000 for a typical 300m energized roadbed in just one lane of highway travelling in one direction (Gyuk, 2003). These costs would double in order to provide ICPT infrastructure in just one lane of travel for each direction of travel. The goal is that each section of track will supply a sufficient burst, or pulse, of charge wirelessly to the EV
until the next energized section is reached, thus minimizing EV battery pack size and cost.

In addition to this cost, the cost of the grid converter(s) would have to be taken into account depending on the power level of the system. In determining the cost of these large utility power converters, the EPRI report was used to estimate the cost of grid-level power conversion system (PCS) installations. The PCS includes all components necessary to deliver the electrical energy from the power strips to the Energy Storage System (ESS) on the EV as well as to discharge stored energy to the utility grid. For dynamic on-road ICPT charging, it was determined that this would be Type III PCS for prompt discontinuous operation, which is a short duration power quality (SPQ) application. Although the converter must remain utility connected and powered up in order to energize the roadbed transmit coils when needed, the Type III PCS will have very low standby losses as it is not required to be constantly energized. In other words, the PCS would remain idle until an EV passed over the transmit coils. The PCS can also be used to provide grid reactive power support during its idle time. The total cost of the PCS was estimated using Equation 2:

\[
Type \text{ III PCS Cost} = 365 \cdot P_f^{-0.54}
\]

Equation (2)

Equation 2 was developed from historical data of PCS vendors, and for this case, a pulse factor of 3.5, which was the middle value of the typical 2 to 5 pulse factor range,
was assumed. Therefore, the total cost of the PCS would amount to 185 $/kW. So, a 1MW grid converter for ICPT would be approximately $185,600 fully installed, without including the additional costs associated with the grid point of common connection (PCC) transformer (Gyuk, 2003).

5.2 Cost Issues Associated with ICPT Infrastructure Maintenance

Typically, public agencies, like the DOT, are not only responsible for road construction (highway development programs) but also for road maintenance (rehabilitation programs). With ICPT infrastructure being introduced into the scenario, however, there are a number of added costs associated with the maintenance of the highway infrastructure. The initial problem in dealing with the ICPT infrastructure is that the DOT’s pavement management schedules and costs will significantly change. There must be significant amounts of coordination between the DOT’s pavement management schedules and the electric utility’s power strip management schedules. It will take significant amounts of costs to train employees in managing the complex ICPT system as well as additional time and costs in efficiently merging both management database systems used to monitor the pavement and the ICPT infrastructures.

ICPT infrastructure in the pavement itself consists of the transmit coils in the roadbed, which are used to power the EVs. Although these transmit coils can be installed in both asphalt or concrete pavements, most previous work has investigated application in concrete pavement. These works have found that transmit coils should be installed directly above any re-bar so as to minimize parasitic losses and that at frequencies of
ICPT interest, concrete pavement is mainly resistive, due to its resistive-capacitive (R-C) character. As a result, this loss appears to the grid converter as a continuous loss during energized periods which is directly comparable to the line losses on transmission and distribution lines that utilities currently face, which is simply a cost of doing business (Gyuk, 2003). Other studies have found that these roadway embedded coils, or continuous system cables, should be suitable for the lifecycle of the concrete roadbed. Typically, the coils are installed as long sections of pre-stressed and reinforced concrete modules having transmit coils and attachment cables and then are typically overlaid with synthetic concrete or some plasticizer, much like the interconnected pre-stressed sections of guide way used in China’s construction of the Shanghai MAGLEV train by the Shanghai Maglev Transportation Development Company (2005). These sections, while not protected by the roadbed reinforcement rods, are not installed in the lane wheel ruts left by large over-the-road trucks, and thus, may not require significant amounts of maintenance or replacement. Therefore, while it may appear that typical maintenance costs will remain low for the ICPT infrastructure itself, costs may begin to accumulate in training personnel in maintaining the new technology as well as in hiring more DOT personnel to monitor the pavement infrastructure so as to insure that the ICPT embedded modules are not exposed to harmful conditions due to roadway deterioration.

Other operational issues will include resilience to snow plows in colder regions. Similar to raised pavement markers or inductive loop detectors, any charging infrastructure near the pavement surface can expect harsh conditions throughout winter months in colder climates. In particular, ICPT infrastructure maintenance costs may
significantly increase if coils are frequently disabled by winter maintenance activities such as plowing and salting roads. In addition, it may be necessary to install additional equipment into the infrastructure that will heat ICPT components in winter and cool ICPT components in summer in order to protect the system from adverse weather conditions.

5.3 Cost Issues Associated with ICPT Infrastructure Operations

When dealing with the operational cost of the ICPT infrastructure, both the DOT and even the utility companies will have numerous cost issues to consider. ICPT infrastructure must remain operationally stable and reliable. A stable grid will have balanced power generation throughout normal and abnormal conditions; a reliable grid will be able to handle unexpected demands without failing and be able to quickly recover if failure does occur for some unforeseen reason (Kezunovic et al., 2010). The utility companies’ major costs will arise in distribution system expansion costs in order to ensure stability and reliability within the electric grid. The estimated full cost of upgrades to the grid network in order to bring the generation on line is approximately $700/kW for transmission and distribution (T&D) costs and $70/kW-yr in peak generation costs (Silver Spring Networks, 2010). In order to anticipate the scale of such costs, utilities must perform what is known as power system planning. The objective of such efforts is to strategically plan for the long-range expansion of the generation, transmission, and distribution systems in order to meet the added energy demand that EVs place on the utility grid. The goal is to supply an adequate amount of ICPT infrastructure capable of
meeting the predicted future load forecast while also minimizing ICPT infrastructure expansion costs. The utility companies must account for both economic factors and load requirements in calculating distribution system expansion costs (Wenyuan, 1993). The major issue that arises here is that the future electrical load is very difficult to predict as many variables will determine how quickly and to what extent EVs will penetrate the transportation sector.

Smart-charging management is one strategy that the utility companies may consider while trying to ensure that the electric grid is able to meet EV energy demands. The utilities are able to reduce peak demand through smart-charging processes such as time-of-use rates and load control (Silver Springs Networks, 2010). Time-of-use rates is essentially a type of demand response control in which EVs are charged a higher $/kW rate during peak hours in order to control the load during hours where demand is the highest and to avoid severe situations like the northeastern United States blackout in 2003, which resulted in billion dollar losses (U.S.-Canada Power System Outage Task Force, 2003). In addition, electric utilities can use load scheduling, a process that allows them to balance energy supply and demand in real-time. It will also allow utilities to reduce energy costs by using more renewable energy sources as load scheduling matches charging demand to irregular renewable generation supply, such as wind and solar energy (Silver Spring Networks, 2010). Pricing schemes like these will help utility companies reduce their new generation, transmission, and distribution costs.

In order to ensure optimum operational efficiency in an ICPT system, the location of the ICPT track needs to be strategically positioned within the pavement depth so as to
minimize the operational costs. In other words, the goal is to maximize the efficiency of ICPT operations so that neither the public utility companies nor EV drivers experience increased costs from unused energy lost in the charging process. In order to maximize the charging efficiency, the ICPT power strips should be positioned as close to the ESS on the EV as possible, ideally on the pavement surface. On the contrary, the track should be positioned in the pavement deep enough so it is not damaged by traffic and the environment as surface pavement deterioration in the roadway occurs. The ICPT track should be in such a location that the energy transfer from the road to the vehicle’s battery pack is optimized. One constraint with an ICPT system is that the tracks are most efficient and cost effective when placed on continuous roads, such as highways and interstates, and may not be optimal for road environments where drivers may be changing routes frequently (Lorico, 2011). In addition, efficiency depends heavily on the alignment between the infrastructure power strip and EV power receiver, thus drivers navigating in the lane center receive the most efficient charge. This alignment issue could be optimized by driver assistance but may also add additional cost to the EV.

To accommodate these limitations, construction of an EV only lane is another cost-efficient alternative that DOTs could consider for installing ICPT infrastructure as upgrading all travel lanes would require significant costs. The feasibility of such a lane will depend heavily on a number of factors including cost, operational efficiency, and accessibility. EV drivers are more likely to use such facilities if they are both convenient to use as well as economically practical. Beyond facilitating EV traffic, EV only lanes will improve traffic operation and safety on other lanes by splitting the EV traffic from
other traffic and will allow the EV drivers to put more focus on properly aligning the EV receiver with the ICPT transmitter while driving. An ideal option that DOTs should consider is placing these ICPT charging lanes at interstate toll stations where traffic must slow down and are able to select a specific travel lane. The long approach on the collector lanes may be ideal for in-motion charging. By having this separate lane, EVs are able to focus on driving on the tracks, thus improving charging efficiency while also not being a hindrance to other drivers outside of the ICPT system.

In addition to the physical costs of operating the infrastructure itself, DOTs and utility companies must also be prepared to handle the costs associated with educating and training all personnel in operating the new ICPT infrastructure. ICPT systems are complex and require advanced expertise acquired only through intensive training; therefore, the stakeholders must implement training programs to educate their personnel, something that will be very time consuming and expensive.

5.4 Proposed Business Model to Fund ICPT Infrastructure Costs

The United States will benefit greatly through the successful implementation of ICPT infrastructure that will propel EV market penetration to the next level and bring our transportation system into the future. The development and integration of an ICPT system, however, will create a new and radically different business model for the DOT. The DOT has already experienced significant shortfalls in funding from the federal gas tax as passenger vehicles have become more and more fuel efficient, and with integration
of EVs into the transportation sector, this lack of funding will only increase (Texas Transportation Institute, 2010).

In this section, a new business model is proposed for the DOT in efforts of successfully funding the construction, maintenance, and operation of ICPT infrastructure. The business model leads to the development of a joint company that would be responsible for constructing, maintaining, and operating the ICPT infrastructure. This proposed joint company should be utilized throughout the entire lifespan of the ICPT infrastructure to facilitate the raising of funds needed to maintain and operate it throughout the years to come. This plan would allow the DOT to maintain the infrastructure based on a standard architecture they devise (similar to the national ITS architecture), while the utility company, or the EV service provider, would then be held responsible for providing the electrical energy and charging the EV drivers according to their electrical usage (Chowdhury et al., 2003). Figure 5.1 is a conceptual flow chart of this proposed business model. The chart shows that the main participants will include the transportation network users, the DOT, the utility companies, and other private companies.
In the proposed business model, the DOT and the electric service provider, or the utility company, must be prepared to fund the significantly large initial construction costs of the ICPT infrastructure required for in-motion power transfer of electric vehicles. The DOT would enter into a joint contract with the utility company and with other interested private investors in what is known as public-private partnerships (PPPs). In addition to supporting the initial costs of the ICPT infrastructure, the DOT would maintain set standards for the highway infrastructure, while the utility companies would ensure that the ICPT tracks themselves were properly maintained. The major benefit of this business strategy for the DOT is that they are able to maintain their centralized role in managing the transportation network, much like the way intelligent transportation system (ITS)
infrastructure is currently installed, while still receiving significant amounts of aid in funding the system. It is critical however, that the DOTs solicit the funding of other private businesses into the services it provides as a way to pull in outside resources that could be used to maintain the current system and invest in expanded infrastructure. The DOT can use PPPs as a powerful financial tool capable of raising significant amounts of revenue for its transportation needs. Historically, public agencies have not done a good job utilizing PPPs as reported by the Texas DOT in 2007 that only $8 billion of the $700 billion available revenue were actually utilized in public transportation projects (Texas Department of Transportation, 2007).

In this business strategy, both the non-EV and EV drivers would pay to use the highway infrastructure and ICPT infrastructure respectively. The non-EV drivers would be charged based on a road-usage fee, or a pay-per-mile contract, with the DOT. These road-use charges (RUCs) would be based on vehicle-miles travelled (VMT) and could be tracked with current technologies such as Geographical Positioning System (GPS) devices (Whitty, 2007). This fee could also be viewed as a penalty for not driving zero-emission vehicles. In addition, the EV drivers could also be charged a road usage fee, but the fee could be substantial lower than for gasoline powered vehicles. The EV drivers would pay thru a charging subscription plan with the electric utility company. They would be charged for the energy received through the ICPT power strips, similar to the E-ZPass automatic, electronic toll collection system that currently allows traffic to travel through toll facilities quickly and efficiently (E-ZPass, 2011). This type of “smart grid internet for electricity” has also attracted numerous private investors, including auto
maker companies like GM, Ford, Toyota, and Nissan, as well as several information technology companies like IBM, Google, Cisco, and Microsoft (Addison, 2009). The utilities would then give a predetermined share of this revenue from the subscription plans to the DOT to help maintain the transportation network, specifically the ICPT infrastructure. In addition, congestion pricing and toll roads for all users in the highway system can provide a demand management approach to traffic congestion while also generating extra revenue to support highway infrastructure like the ICPT systems.

Other government policies that are being taken to promote and reward the savings that EV technologies generate include: monetary bonuses for reducing carbon dioxide emissions, government sponsored warranties for batteries and charging station infrastructure, and numerous tax credits for both EV and EV infrastructure construction (Fontaine, 2008). As the number of users in the system increases, the ICPT infrastructure will be better-funded and thus better supported and maintained. Cost to EV drivers will be linked mainly to the scope of the implementation of ICPT infrastructure and the number of users that will actually use the system. Critical factors for EV user support of the system will be based on the effectiveness and reliability of the ICPT infrastructure as that is the technology needed to overcome the current market barriers of EV technology, such as range anxiety and EV’s limited range.
CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Through simulation, this study evaluated how connected vehicle technologies could effectively facilitate the EV charging process. The research evaluated the efficacy of EV charging operations with and without connected vehicle capabilities and found that there were benefits when connected vehicle technologies were integrated with EV technologies. By simulating a traffic network of EVs in Matlab, it was found that the battery charging process was optimized for EVs that were able to use connected vehicle communications to directly receive information regarding current CS length of queues and waiting time conditions.

The analysis was performed for the optimization of total time for the EV to recharge, which would also have significant impacts on two vehicle parameters: extra time spent travelling to the CS and time spent in the CS queue, as well as two CS parameters: queue length and power output as related to fast-charging. This study demonstrated that with increasing levels of connected vehicle communication, optimization regarding total travel time and distribution of the EVs throughout the entire network would occur. Through connected vehicle technologies, the EV drivers incurred substantial time-savings, and the electrical load was evenly distributed throughout the entire network. The average extra time due to charging and the average time in the queue were significantly shorter for the connected EV case as compared to a non-connected
case in which the driver chooses the nearest CS. Even more, greatest savings were incurred when the connected EV was able to receive a CS assignment in real-time according to the network and CS condition at every time step instead of just receiving one CS assignment prior to beginning the charging process.

In addition, the connected vehicle technologies would also help the utility companies load balance the electric grid as these technologies would route EVs to locations experiencing lower electricity demand, which are essentially the CSs with the smallest queue lengths. The EVs were thus evenly distributed throughout the network, and as a result, the queue lengths at each CS were minimized and the power output throughout the network was also evenly distributed, not resulting in power overloads at any one station.

There still remains much research to be done on how to successfully manage EV battery energy for real-time traffic conditions. This study could be expanded to address the problems faced while trying to optimize the vehicle’s range based on current traffic situations and driver behavior. The goal of such research would aim to implement connected vehicle technologies in such a manner that EVs would be rerouted to the optimum CS based on the vehicle’s current energy reserve during times of congestion in the traffic network.

Further research could also be done in efforts of implementing a line of communication between the utility companies and the connected vehicle network in which information on the current grid load is exchanged. Connected vehicle technologies would allow the utility companies to monitor the real-time load at each CS location and
to adjust the cost of the electricity accordingly. Essentially, dynamic pricing through connected vehicle technologies could influence both the demand and the decision as to where and when an EV will charge. By doing so, connected vehicle technologies could then inform drivers on the real-time cost at each CS. In connected EVs, the roadside controller would direct the EV to the CS that would result in the minimum cost for a recharge in terms of dollars per mile. This study can be expanded by simulating the different dynamic pricing scenarios described above.

Apart from the cost savings, connected vehicle technologies will also help the utilities load balance the electric grid since they can offer lower prices at locations experiencing lower electricity demand. This in turns helps the utility companies avoid failure of a portion of the electric grid due to excessive demand resulting in the failure of the associated transformer. These real-time traffic situations are complex in nature and require a unique, detailed energy management strategy utilizing the benefits of connected vehicle and infrastructure technologies in order to fully optimize energy efficiency and to address issues like range anxiety and charging demand.

The key challenge in making ICPT infrastructure readily available for EV drivers lies in the fact that such infrastructure has large construction, maintenance, and operational costs. ICPT charging, like other EV charging schemes, has its advantages and disadvantages; however, when it is fully integrated into the transportation network, it will theoretically give EVs an indefinite driving range while still minimizing battery costs. As found in this research through an analysis of available information, ICPT infrastructure will foster EV market penetration by providing fast, reliable charging of the
EV battery; however, in order to create such a network, much collaboration between stakeholders will be needed in order to fund the expensive ICPT infrastructure. It is vital that all stakeholders collaborate together and combine their expertise and resources in order to maximize the benefits of the ICPT system for facilitating EV charging operations.

The unique business aspect of the proposed business model allows for the DOT to utilize services and revenue from other stakeholders such as utility companies, EV and non-EV drivers, and other interested private companies while still maintaining control over the construction and direction of what could be a very powerful and influential system for the market penetration of EVs. By sharing the costs with other stakeholders, this business model could produce a way to finance the development of ICPT infrastructure, and once developed, the system could remain self-supporting once the EV market penetration level becomes large enough. For this business model, it would be most economically feasible to implement ICPT infrastructure in targeted large cities where EV densities are the highest. From there, the infrastructure could expand outward to arterials and into smaller cities as the market penetration level of EVs continued to increase.

This research can be expanded further by collecting more concrete data through real world experiments on real driving scenarios. The goal of such research would be to quantify the benefits of ICPT infrastructure with EV’s with reduced capacity batteries versus fast charging infrastructure with EV’s with long range batteries in a real world traffic environment. Although further research into the feasibility and technical aspects of
inductively coupled power transfer for electric vehicles is needed, the DOTs must begin today determining an acceptable penetration level of EVs needed to justify the cost of such expensive ICPT infrastructure that has the potential of making the United States’ transportation sector more sustainable.

6.2 Recommendations

- Electric grid simulations, which can simulate demand and supply under varying probable real life scenarios, should be integrated with connected vehicle and EV simulations. The connected vehicle system should have an interface with the electricity grid management center in order to help utility companies load balance the grid in real-time and to aid in implementing innovative demand management strategies such as dynamic pricing.

- Currently, most of the research and development regarding EV infrastructure is being carried out within the private and/or utility industries. State and local Departments of Transportations should also actively participate in the EV infrastructure planning and deployment phases in order to facilitate coordination and efficient resource sharing.

- Future research can look at operational impacts of Inductively Coupled Power Transfer for EVs supported by connected vehicles. Because this new charging scheme is unfamiliar to drivers, connected vehicles can potentially provide increased driver confidence and charging efficiency throughout the ICPT process.
Future work should carefully evaluate the costs and benefits of EV operations. The economic, environmental, and time-saving benefits must be carefully compared with the costs of producing electricity and the costs associated with EV technologies, such as infrastructure costs and vehicle costs, in efforts of increasing EV market penetration and promoting the creation of EV policies and standards.
APPENDIX

MATLAB PROGRAM
Initialization (initial.m): Create the data structure for charging stations and vehicles

% create charging station and vehicle data
clear
% 40*40
% 5 links away, not on the edge, total # of stations:49
charging_station(49)=struct('ID',[],'coord',[],'wait_time',[],'demand_queue',[],'eta',[],'etl',[]
,'demand_t',[],'actual_queue',[],'actual_t',[],'charging',[],'output',[],'Ccost',[],'output_p',[]);
for i = 1:length(charging_station)
    charging_station(i).ID = i;
    x = (mod(i-1,7) + 1) * 5;
    y = (i - (mod(i-1,7) + 1)) / 7 * 5 + 5;
    charging_station(i).coord = [x y];
    charging_station(i).wait_time = 0;  % total time to charge all the vehicle
    currently in the actual queue
    charging_station(i).demand_t = zeros(1,72000);
    charging_station(i).actual_t = zeros(1,72000);
    charging_station(i).charging = 0;
    charging_station(i).output_p = 0;
end
save CS_base_40 charging_station

clear
% 35*35
% 5 links away, not on the edge, total # of stations:36
charging_station(36)=struct('ID',[],'coord',[],'wait_time',[],'demand_queue',[],'eta',[],'etl',[]
,'demand_t',[],'actual_queue',[],'actual_t',[],'charging',[],'output',[],'Ccost',[],'output_p',[]);
for i = 1:length(charging_station)
    charging_station(i).ID = i;
    x = (mod(i-1,6) + 1) * 5;
    y = (i - (mod(i-1,6) + 1)) / 6 * 5 + 5;
    charging_station(i).coord = [x y];
    charging_station(i).wait_time = 0;  % total time to charge all the vehicle
    currently in the actual queue
    charging_station(i).demand_t = zeros(1,72000);
    charging_station(i).actual_t = zeros(1,72000);
    charging_station(i).charging = 0;
    charging_station(i).output_p = 0;
end
save CS_base_35 charging_station

clear
% 30*30
% 5 links away, not on the edge, total # of stations:25
charging_station(25)=struct('ID',[],'coord',[],'wait_time',[],'demand_queue',[],'eta',[],'etl',[]
,'demand_t',[],'actual_queue',[],'actual_t',[],'charging',[],'output',[],'Ccost',[],'output_p',[]);

for i = 1:length(charging_station)
    charging_station(i).ID = i;
    x = (mod(i-1,5) + 1) * 5;
    y = (i - (mod(i-1,5) + 1)) / 5 * 5 + 5;
    charging_station(i).coord = [x y];
    charging_station(i).wait_time = 0;  % total time to charge all the vehicle
CURRENTLY in the ACTUAL QUEUE
    charging_station(i).demand_t = zeros(1,72000);
    charging_station(i).actual_t = zeros(1,72000);
    charging_station(i).charging = 0;
    charging_station(i).output_p = 0;
end

save CS_base_30 charging_station

clear
% create vehicles and OD
% for two hours, assume one veh/sec
veh(2000)=struct('ID',[],'status',[],'SOC',[],'des',[],'origin',[],'current',[],'CS',[],'TTTwc',[],'
TTTwoc',[],'TIQ',[],'Ccost',[]);
% CS: assigned charging station coordinate, TTTwc: total travel time with
% charging, TTTwoc: total travel time without charging, TIQ: time in the
% queue, Ccost: charging cost

for i = 1:length(veh)
    veh(i).ID = i;
    veh(i).status = 1;
    switch mod(i,4)
        case 0  % from x=0
            veh(i).origin = [0,round(rand*40)];
            veh(i).des = [40,round(rand*40)];
        case 1  % from y=0
            veh(i).origin = [round(rand*40),0];
            veh(i).des = [round(rand*40),40];
        case 2  % from x = 40
            veh(i).origin = [40,round(rand*40)];
            veh(i).des = [0,round(rand*40)];
        case 3  % from y = 40
            veh(i).origin = [round(rand*40),40];
            veh(i).des = [0,round(rand*40)];
    end
veh(i).origin = [40,round(rand*40)];
veh(i).des = [0,round(rand*40)];
case 3 % from y = 40
veh(i).origin = [round(rand*40),40];
veh(i).des = [0,round(rand*40)];
otherwise
  'error'
end

veh(i).current = veh(i).origin;
veh(i).CS = 0;
veh(i).TTTwoc = sum(abs(veh(i).des-veh(i).origin)) *2 ;
veh(i).SOC = round(rand * 20 + 20);  % randomly from 20 to 40 miles
veh(i).TTTwc = 0;
veh(i).TIQ = 0;

end

save veh_base_40 veh

% 30
for i = 1:length(veh)
  veh(i).ID = i;
  veh(i).status = 1;
  switch mod(i,4)
    case 0  % from x=0
      veh(i).origin = [0,round(rand*30)];
      veh(i).des = [30,round(rand*30)];
    case 1 % from y=0
      veh(i).origin = [round(rand*30),0];
      veh(i).des = [round(rand*30),30];
    case 2 % from x = 30
      veh(i).origin = [30,round(rand*30)];
      veh(i).des = [0,round(rand*30)];
    case 3 % from y = 30
      veh(i).origin = [round(rand*30),30];
      veh(i).des = [0,round(rand*30)];
    otherwise
      'error'
  end

  veh(i).current = veh(i).origin;
  veh(i).CS = 0;
  veh(i).TTTwoc = sum(abs(veh(i).des-veh(i).origin)) *2 ;
veh(i).SOC = round(rand * 20 + 10);  % randomly from 10 to 30 miles
veh(i).TTTwc = 0;
veh(i).TIQ = 0;
end

save veh_base_30 veh

% 35
for i = 1:length(veh)
    veh(i).ID = i;
    veh(i).status = 1;
    switch mod(i,4)
        case 0  % from x=0
            veh(i).origin = [0,round(rand*35)];
            veh(i).des = [35,round(rand*35)];
        case 1 % from y=0
            veh(i).origin = [round(rand*35),0];
            veh(i).des = [round(rand*35),35];
        case 2 % from x = 35
            veh(i).origin = [35,round(rand*35)];
            veh(i).des = [0,round(rand*35)];
        case 3 % from y = 35
            veh(i).origin = [round(rand*35),35];
            veh(i).des = [0,round(rand*35)];
        otherwise
            'error'
    end
    veh(i).current = veh(i).origin;
    veh(i).CS = 0;
    veh(i).TTTwc = sum(abs(veh(i).des-veh(i).origin)) *2 ;
    veh(i).SOC = round(rand * 20 + 15);  % randomly from 15 to 35 miles
    veh(i).TTTwc = 0;
    veh(i).TIQ = 0;
end

save veh_base_35 veh
Vehicle function for Case 0 (vehicle0.m)

function [ veh_struct, charge_station ] = vehicle0( veh_struct, charge_station )
% VEH move veh every second considering shortest route and charging
% [] = veh(veh_struct, charge_station)
% veh_struct.ID: vehicle ID
% veh_struct.status: 0 normal driving, 1 need recharge (no CS assigned),
% 2 on the way to charging station, 3 wait in queue, 4 charging;
% veh_struct.SOC: 100 miles is full;
% veh_struct.current: current node (x,y);
% veh_struct.des: destination node (x,y);
% veh_struct.CS: charging station assigned, 0 for no assignment;
%
% charge_station.ID: charge station ID
% charge_station.coord: station node (x,y);
% charge_station.actual_queue: IDs for vehicles at the station
% charge_station.demand_queue: IDs for all vehicles
% charge_station.charging: ID for vehicles which are charging, two vehicles at a time
% charge_station.wait_time: waiting time

if sum(abs(veh_struct.current - veh_struct.des)) ~= 0  % not reach des
    energy_need = sum(abs(veh_struct.des - veh_struct.current));  % each link is 1 mile,
    need 1 mile SOC

    switch veh_struct.status

        case 0  % normal driving
                veh_struct.current = move_veh(veh_struct.current, veh_struct.des);
                veh_struct.SOC = veh_struct.SOC - 1;

        case 1  % need assign charging station
                veh_struct.CS = assign_CS(veh_struct, charge_station);
                charge_station(veh_struct.CS).demand_queue =
                add_queue(veh_struct.ID, charge_station(veh_struct.CS).demand_queue);  % add vehicle
                to demand queue of assigned station

                if sum(abs(veh_struct.current - charge_station(veh_struct.CS).coord)) ~= 0  %
                moving to CS
                    veh_struct.status = 2;  % CS is assigned

        end
    end
end

66
veh_struct.current = move_veh(veh_struct.current, charge_station(veh_struct.CS).coord);
veh_struct.SOC = veh_struct.SOC - 1;

else  % already at the CS

% no queue
if isempty(charge_station(veh_struct.CS).actual_queue) &&
charge_station(veh_struct.CS).charging == 0  % can start charging in next second

veh_struct.status = 4;
charge_station(veh_struct.CS).charging = veh_struct.ID;
charge_station(veh_struct.CS).wait_time = ceil((energy_need + 5) * 15 / 200) * 2;

else % wait in queue

veh_struct.status = 3;
charge_station(veh_struct.CS).actual_queue =
add_queue(veh_struct.ID,charge_station(veh_struct.CS).actual_queue);  % add vehicle to
actual queue
veh_struct.TIQ = veh_struct.TIQ + 2;
charge_station(veh_struct.CS).wait_time =
charge_station(veh_struct.CS).wait_time + ceil((energy_need + 5) * 15 / 200) * 2;

end

end

% case 2 % moving to CS

if sum(abs(veh_struct.current-charge_station(veh_struct.CS).coord))~=0

veh_struct.current = move_veh(veh_struct.current, charge_station(veh_struct.CS).coord);
veh_struct.SOC = veh_struct.SOC - 1;

else  % already at the CS

if isempty(charge_station(veh_struct.CS).actual_queue) &&
charge_station(veh_struct.CS).charging == 0  % can start charging in next second

veh_struct.status = 4;
charge_station(veh_struct.CS).charging = veh_struct.ID;

charge_station(veh_struct.CS).wait_time = ceil((energy_need + 5) * 15 / 200) * 2;

else

    veh_struct.status = 3;
    charge_station(veh_struct.CS).actual_queue = add_queue(veh_struct.ID,charge_station(veh_struct.CS).actual_queue); % add vehicle to actual queue
    veh_struct.TIQ = veh_struct.TIQ + 2;
    charge_station(veh_struct.CS).wait_time = charge_station(veh_struct.CS).wait_time + ceil((energy_need + 5) * 15 / 200) * 2;

end

end

case 3 % wait in queue

    if charge_station(veh_struct.CS).charging== 0 &&
    charge_station(veh_struct.CS).actual_queue(1)==veh_struct.ID % if there is an empty spot and first of the queue
        veh_struct.status = 4;
        charge_station(veh_struct.CS).actual_queue(1)=[]; %remove from the actual queue
        charge_station(veh_struct.CS).charging = veh_struct.ID; % start charging in next second
    else
        veh_struct.TIQ = veh_struct.TIQ + 2;
    end

case 4 % charging

    if veh_struct.SOC - energy_need >= 5 % enough SOC to finish the trip (5 miles clearance)
        veh_struct.status = 0;
        charge_station(veh_struct.CS).charging = 0; %remove from charging
charge_station(veh_struct.CS).demand_queue(charge_station(veh_struct.CS).demand_queue==veh_struct.ID)=[ ]; %remove from demand queue

    % start moving to des
    veh_struct.current = move_veh(veh_struct.current, veh_struct.des);
    veh_struct.SOC = veh_struct.SOC - 1;

else % charging

    veh_struct.SOC = veh_struct.SOC + 100/7.5;
    charge_station(veh_struct.CS).output_p = charge_station(veh_struct.CS).output_p + 100/7.5;
    charge_station(veh_struct.CS).wait_time = charge_station(veh_struct.CS).wait_time - 2;

    end

otherwise

    'error'

end

veh_struct.TTTwc = veh_struct.TTTwc + 2;

end

end

function [current] = move_veh(current, des)
% des and current are in [x y] format
temp = des - current;

if temp(1)~=0 & & temp(2)==0
    if rand <=0.5 % randomly move on x or y direction
        current = current + sign(temp(1))*[1 0];
    else
        current = current + sign(temp(2))*[0 1];
    end
else % temp(1)==0 or temp(2)==0

    current = current + sign(temp(1))*[1 0] + sign(temp(2))*[0 1];

end
function [queue]=add_queue(ID,queue)
% add a veh to queue
if ~isempty(queue)
    queue = [queue ID];
else
    queue = ID;
end
end

classdef ChargeStation
    properties
        coord
        ID
    end
    methods
        function [ID] = assign_CS(veh, charge_station)
% return the coordinate of best charging station
        range = veh.SOC;
        min_cost = inf;
        for i = 1:length(charge_station)
            if sum(abs(veh.current - charge_station(i).coord)) <= range
                if sum(abs(veh.current - charge_station(i).coord)) < min_cost
                    min_cost = sum(abs(veh.current - charge_station(i).coord));
                    ID = charge_station(i).ID;
                elseif sum(abs(veh.current - charge_station(i).coord)) == min_cost && rand > 0.5
                    % in case there are more than one best solution, 50% replace selection
                    min_cost = sum(abs(veh.current - charge_station(i).coord));
                    ID = charge_station(i).ID;
                end
            end
        end
    end
end
Vehicle function for Case 1 (vehicle1.m)

function [ veh_struct, charge_station ] = vehicle1( veh_struct, charge_station )
% VEH move veh every second considering shortest route and charging
% [] = veh(veh_struct, charge_station)
% veh_struct.ID: vehicle ID
% veh_struct.status: 0 normal driving, 1 need recharge(no CS assigned),
% 2 on the way to charging station, 3 wait in queue, 4 charging;
% veh_struct.SOC: 100 miles is full;
% veh_struct.current: current node (x,y);
% veh_struct.des: destination node (x,y);
% veh_struct.CS: charging station assigned, 0 for no assignment;
% charge_station.ID: charge station ID
% charge_station.coord: station node (x,y);
% charge_station.actual_queue: IDs for vehicles at the station
% charge_station.demand_queue: IDs for all vehicles
% charge_station.charging: ID for vehicles which are charging, one vehicle at a time
% charge_station.wait_time: waiting time

if sum(abs(veh_struct.current - veh_struct.des))~=0  % not reach des
    energy_need = sum(abs(veh_struct.des - veh_struct.current));  % each link is 1 mile, need 1 mile SOC
    switch veh_struct.status
        case 0  % normal driving
            veh_struct.current = move_veh(veh_struct.current, veh_struct.des);
            veh_struct.SOC = veh_struct.SOC - 1;
        case 1 % need assign charging station
            veh_struct.CS = assign_CS(veh_struct, charge_station);
            charge_station(veh_struct.CS).demand_queue =
                add_queue(veh_struct.ID, charge_station(veh_struct.CS).demand_queue);  % add vehicle to demand queue of assigned station
            if sum(abs(veh_struct.current - charge_station(veh_struct.CS).coord))~=0  % moving to CS
                veh_struct.status = 2;  % CS is assigned
                veh_struct.current = move_veh(veh_struct.current, charge_station(veh_struct.CS).coord);
            end
        end
    end
else
    % already reach des
end
veh_struct.SOC = veh_struct.SOC - 1;

else  % already at the CS

    if isempty(charge_station(veh_struct.CS).actual_queue) &&
    charge_station(veh_struct.CS).charging==0 % can start charging in next second

        veh_struct.status = 4;
        charge_station(veh_struct.CS).charging = veh_struct.ID;
        charge_station(veh_struct.CS).wait_time = ceil((energy_need + 5) * 15 / 200) * 2;
    
    else

        veh_struct.status = 3;
        charge_station(veh_struct.CS).actual_queue =
        add_queue(veh_struct.ID,charge_station(veh_struct.CS).actual_queue); % add vehicle to
        actual queue
        veh_struct.TIQ = veh_struct.TIQ + 2;
        charge_station(veh_struct.CS).wait_time =
        charge_station(veh_struct.CS).wait_time + ceil((energy_need + 5) * 15 / 200) * 2;
    
    end

end

case 2 % moving to CS

    if sum(abs(veh_struct.current-charge_station(veh_struct.CS).coord))~=0

        veh_struct.current = move_veh(veh_struct.current,
        charge_station(veh_struct.CS).coord);
        veh_struct.SOC = veh_struct.SOC - 1;

    else % already at the CS

        if isempty(charge_station(veh_struct.CS).actual_queue) &&
        charge_station(veh_struct.CS).charging==0 % can start charging in next second

            veh_struct.status = 4;
            charge_station(veh_struct.CS).charging = veh_struct.ID;
            charge_station(veh_struct.CS).wait_time = ceil((energy_need + 5) * 15 / 200) * 2;

        end

    end
else
    veh_struct.status = 3;
    charge_station(veh_struct.CS).actual_queue =
    add_queue(veh_struct.ID,charge_station(veh_struct.CS).actual_queue); % add vehicle to
    actual queue
    veh_struct.TIQ = veh_struct.TIQ + 2;
    charge_station(veh_struct.CS).wait_time =
    charge_station(veh_struct.CS).wait_time + ceil((energy_need + 5) * 15 / 200) * 2;
end
end

case 3 % wait in queue
    if charge_station(veh_struct.CS).charging== 0 &&
     charge_station(veh_struct.CS).actual_queue(1)==veh_struct.ID   % if there is an empty
     spot and first of the queue
        veh_struct.status = 4;
        charge_station(veh_struct.CS).actual_queue(1)=[]; %remove from the actual
     queue
        charge_station(veh_struct.CS).charging = veh_struct.ID;  % start charging in
     next second
    else
        veh_struct.TIQ = veh_struct.TIQ + 2;
    end
end

case 4 % charging
    if veh_struct.SOC - energy_need >=5  % enough SOC to finish the trip (5 miles
     clearance)
        veh_struct.status = 0;
        charge_station(veh_struct.CS).charging = 0; %remove from charging
    charge_station(veh_struct.CS).demand_queue(charge_station(veh_struct.CS).demand_qu
     eue==veh_struct.ID)=[]; %remove from demand queue
    % start moving to des
veh_struct.current = move_veh(veh_struct.current, veh_struct.des);
veh_struct.SOC = veh_struct.SOC - 1;

else  % charging

    veh_struct.SOC = veh_struct.SOC + 100/7.5;
    charge_station(veh_struct.CS).output_p =
    charge_station(veh_struct.CS).output_p + 100/7.5;
    charge_station(veh_struct.CS).wait_time =
    charge_station(veh_struct.CS).wait_time - 2;

end

otherwise

'error'
end

veh_struct.TTTwc = veh_struct.TTTwc + 2;
end
end

function [current] = move_veh(current, des)
% des and current are in [x y] format
temp = des - current;

if  temp(1)==0 &&  temp(2)==0
    if rand <=0.5  %randomly move on x or y direction
        current = current + sign(temp(1))*[1 0];
    else
        current = current + sign(temp(2))*[0 1];
    end
else  % temp(1)==0 or temp(2)==0

    current = current + sign(temp(1))*[1 0] + sign(temp(2))*[0 1];
end
end
function [queue]=add_queue(ID,queue)
% add a veh to queue
if ~isempty(queue)
    queue = [queue ID];
else
    queue = ID;
end
end

function [ID] = assign_CS(veh, charge_station)
% return the ID of best charging station
range = veh.SOC;
min_cost = inf;

for i = 1:length(charge_station)
    if sum(abs(veh.current - charge_station(i).coord)) <= range
        cost_t = sum(abs(veh.current - charge_station(i).coord)) * 2; % time to station
        cost_t = cost_t + charge_station(i).wait_time + ceil((sum(abs(veh.des - charge_station(i).coord)+ abs(veh.current - charge_station(i).coord)) - veh.SOC) *15 / 200) * 2;
        % time in the station: wait time + charge time
        cost_t = cost_t + sum(abs(veh.des - charge_station(i).coord)) * 2;
        if cost_t < min_cost
            min_cost = cost_t;
            ID = charge_station(i).ID;
        elseif cost_t == min_cost && rand > 0.5  % in case there are more than one best
            solution, 50% replace selection
                min_cost = cost_t;
                ID = charge_station(i).ID;
        end
    end
end
Vehicle function for Case 2 (vehcile2.m)

function [ veh_struct, charge_station ] = vehicle2( veh_struct, charge_station )
% VEH move veh every second considering shortest route and charging
% []=veh(veh_struct, charge_station)
% veh_struct.ID: vehicle ID
% veh_struct.status: 0 normal driving, 1 need recharge(no CS assigned),
% 2 on the way to charging station,3 wait in queue, 4 charging;
% veh_struct.SOC: 100 miles is full;
% veh_struct.current: current node (x,y);
% veh_struct.des: destination node (x,y);
% veh_struct.CS: charging station assigned, 0 for no assignment;
%
% charge_station.ID: charge station ID
% charge_station.coord: station node (x,y);
% charge_station.actual_queue: IDs for vehicles at the station
% charge_station.demand_queue: IDs for all vehicles
% charge_station.charging: ID for vehicles which are charging, one vehicle at a time
% charge_station.wait_time: waiting time

if sum(abs(veh_struct.current-veh_struct.des))~=0  % not reach des

    energy_need = sum(abs(veh_struct.des-veh_struct.current)); % each link is 1 mile,
    need 1 mile SOC

    switch veh_struct.status

    case 0  % normal driving

        veh_struct.current = move_veh(veh_struct.current, veh_struct.des);
        veh_struct.SOC = veh_struct.SOC - 1;

    case 1 % need assign charging station

        veh_struct.CS = assign_CS(veh_struct,charge_station);
        charge_station(veh_struct.CS).demand_queue =
        add_queue(veh_struct.ID,charge_station(veh_struct.CS).demand_queue); % add vehicle
to demand queue of assigned station

        if sum(abs(veh_struct.current-charge_station(veh_struct.CS).coord))~=0 %
        moving to CS

            veh_struct.status = 2; %CS is assigned

end
end
veh_struct.current = move_veh(veh_struct.current,
charge_station(veh_struct.CS).coord);
veh_struct.SOC = veh_struct.SOC - 1;

else % already at the CS

if isempty(charge_station(veh_struct.CS).actual_queue) &&
charge_station(veh_struct.CS).charging==0 % can start charging in next second

veh_struct.status = 4;
charge_station(veh_struct.CS).charging = veh_struct.ID;
charge_station(veh_struct.CS).wait_time = ceil((energy_need + 5) * 15 /
200) * 2;

else

veh_struct.status = 3;
charge_station(veh_struct.CS).actual_queue =
add_queue(veh_struct.ID,charge_station(veh_struct.CS).actual_queue); % add vehicle to
actual queue
veh_struct.TIQ = veh_struct.TIQ + 2;
charge_station(veh_struct.CS).wait_time =
charge_station(veh_struct.CS).wait_time + ceil((energy_need + 5) * 15 / 200) * 2;

end

end

case 2 % CS has been assigned, moving to CS and reassign CS if better CS exists

new_CS = assign_CS(veh_struct,charge_station);
if new_CS ~= veh_struct.CS

% remove from demand queue of old CS
temp = charge_station(veh_struct.CS).demand_queue;
temp(temp==veh_struct.ID)=[];
charge_station(veh_struct.CS).demand_queue = temp;

% add to demand queue of new CS
veh_struct.CS = new_CS;
charge_station(veh_struct.CS).demand_queue =
add_queue(veh_struct.ID,charge_station(veh_struct.CS).demand_queue);

end
if sum(abs(veh_struct.current-charge_station(veh_struct.CS).coord))~=0

    veh_struct.current = move_veh(veh_struct.current,
    charge_station(veh_struct.CS).coord);
    veh_struct.SOC = veh_struct.SOC - 1;

else % already at the CS

    if isempty(charge_station(veh_struct.CS).actual_queue) &&
    charge_station(veh_struct.CS).charging==0 % can start charging in next second

        veh_struct.status = 4;
        charge_station(veh_struct.CS).charging = veh_struct.ID;
        charge_station(veh_struct.CS).wait_time = ceil((energy_need + 5) * 15 / 
        200) * 2;

    else

        veh_struct.status = 3;
        charge_station(veh_struct.CS).actual_queue =
        add_queue(veh_struct.ID,charge_station(veh_struct.CS).actual_queue); % add vehicle to
        actual queue
        veh_struct.TIQ = veh_struct.TIQ + 2;
        charge_station(veh_struct.CS).wait_time =
        charge_station(veh_struct.CS).wait_time + ceil((energy_need + 5) * 15 / 200) * 2;

    end

end

end

case 3 % wait in queue

    if charge_station(veh_struct.CS).charging== 0 &&
    charge_station(veh_struct.CS).actual_queue(1)==veh_struct.ID % if there is an empty
    spot and first of the queue

        veh_struct.status = 4;
        charge_station(veh_struct.CS).actual_queue(1)=[]; % remove from the actual
        queue
        charge_station(veh_struct.CS).charging = veh_struct.ID; % start charging in
        next second

    else
veh_struct.TIQ = veh_struct.TIQ + 2;

end

case 4 % charging

if veh_struct.SOC - energy_need >= 5 % enough SOC to finish the trip (5 miles clearance)

veh_struct.status = 0;
charge_station(veh_struct.CS).charging = 0; % remove from charging

charge_station(veh_struct.CS).demand_queue(charge_station(veh_struct.CS).demand_queue == veh_struct.ID) = [];

% start moving to des
veh_struct.current = move_veh(veh_struct.current, veh_struct.des);
veh_struct.SOC = veh_struct.SOC - 1;

else % charging

veh_struct.SOC = veh_struct.SOC + 100/7.5;
charge_station(veh_struct.CS).output_p = charge_station(veh_struct.CS).output_p + 100/7.5;
charge_station(veh_struct.CS).wait_time = charge_station(veh_struct.CS).wait_time - 2;

end

otherwise

'error'

end

veh_struct.TTTwc = veh_struct.TTTwc + 2;

end
end

function [current] = move_veh(current, des)
% des and current are in [x y] format
temp = des - current;
if  temp(1)~=0 &&  temp(2)~=0
temp(1) ~= 0  &&  temp(2) ~= 0

if rand <=0.5  %randomly move on x or y direction
    current = current + sign(temp(1))*[1 0];
else
    current = current + sign(temp(2))*[0 1];
end

else  % temp(1)==0 or temp(2)==0

    current = current + sign(temp(1))*[1 0] + sign(temp(2))*[0 1];
end

function [queue]=add_queue(ID,queue)
% add a veh to queue
if ~isempty(queue)
    queue = [queue ID];
else
    queue = ID;
end
end

function [ID] = assign_CS(veh, charge_station)
% return the ID of best charging station
range = veh.SOC;
min_cost = inf;

for i = 1:length(charge_station)
    if sum(abs(veh.current - charge_station(i).coord)) <= range

        cost_t = sum(abs(veh.current - charge_station(i).coord)) * 2; % time to station
        cost_t = cost_t + charge_station(i).wait_time + ceil((sum(abs(veh.des -
charge_station(i).coord)+ abs(veh.current - charge_station(i).coord)) - veh.SOC) *15 / 200) * 2;
        % time in the station: wait time + charge time
        cost_t = cost_t + sum(abs(veh.des - charge_station(i).coord)) * 2;

        if cost_t < min_cost
min_cost = cost_t;
    ID = charge_station(i).ID;
elseif cost_t == min_cost && rand > 0.5  % in case there are more than one best
    solution, 50% replace selection
        min_cost = cost_t;
        ID = charge_station(i).ID;
    end
end
end
end
Vehicle function for Case 3 (vehicle3.m)

function [ veh_struct, charge_station ] = vehicle3( veh_struct, charge_station )
% VEH move veh every second considering shortest route and charging
% [ ]=veh(veh_struct, charge_station)
% veh_struct.ID: vehicle ID
% veh_struct.status: 0 normal driving, 1 need recharge(no CS assigned),
% 2 on the way to charging station, 3 wait in queue, 4 charging;
% veh_struct.SOC: 100 miles is full;
% veh_struct.current: current node (x,y);
% veh_struct.des: destination node (x,y);
% veh_struct.CS: charging station assigned, 0 for no assignment;
% charge_station.ID: charge station ID
% charge_station.coord: station node (x,y);
% charge_station.actual_queue: IDs for vehicles at the station
% charge_station.demand_queue: IDs for all vehicles
% charge_station.eta: eta associates with ID, 0 for at the station
% charge_station.t2c: time to charge associates with ID
% charge_station.charging: ID for vehicles which are charging, one vehicle at a time
% charge_station.wait_time: waiting time
%
if sum(abs(veh_struct.current-veh_struct.des))~=0  % not reach des

    energy_need = sum(abs(veh_struct.des-veh_struct.current));  % each link is 1 mile,
    need 1 mile SOC

    switch veh_struct.status

    case 0  % normal driving

        veh_struct.current = move_veh(veh_struct.current, veh_struct.des);
        veh_struct.SOC = veh_struct.SOC - 1;

    case 1 % need assign charging station

        veh_struct.CS = assign_CS(veh_struct, charge_station);
        temp_time = sum(abs(charge_station(veh_struct.CS).coord-veh_struct.current)) * 2;
        t2c = ceil((sum(abs(veh.des - charge_station(veh_struct.CS).coord)+
                        abs(veh.current - charge_station(veh_struct.CS).coord)) - veh.SOC + 5) * 15 / 200) * 2;
        % sorted by eta

        %

end

end
temp_queue
=sortrows([add_queue(temp_time,charge_station(veh_struct.CS).eta),
add_queue(veh_struct.ID,charge_station(veh_struct.CS).demand_queue),
add_queue(t2c,charge_station(veh_struct.CS).t2c)]);

charge_station(veh_struct.CS).eta = temp_queue(:,1);
charge_station(veh_struct.CS).demand_queue = temp_queue(:,2);
charge_station(veh_struct.CS).t2c = temp_queue(:,3);

if sum(abs(veh_struct.current-charge_station(veh_struct.CS).coord))~=0
    % moving to CS
    veh_struct.status = 2; %CS is assigned
    veh_struct.current = move_veh(veh_struct.current,
    charge_station(veh_struct.CS).coord);
    veh_struct.SOC = veh_struct.SOC - 1;
    temp =
    charge_station(veh_struct.CS).eta(charge_station(veh_struct.CS).demand_queue==veh_s
    truct.ID) - 2;

charge_station(veh_struct.CS).eta(charge_station(veh_struct.CS).demand_queue==veh_s
struct.ID) = temp;

else % already at the CS
    if isempty(charge_station(veh_struct.CS).actual_queue) &&
    charge_station(veh_struct.CS).charging==0 % can start charging in next second
        veh_struct.status = 4;
        charge_station(veh_struct.CS).charging = veh_struct.ID;
        charge_station(veh_struct.CS).wait_time = ceil((energy_need + 5) * 15 /
200) * 2;
    else
        veh_struct.status = 3;
        charge_station(veh_struct.CS).actual_queue =
        add_queue(veh_struct.ID,charge_station(veh_struct.CS).actual_queue); % add vehicle to actual queue
        veh_struct.TIQ = veh_struct.TIQ + 2;
        charge_station(veh_struct.CS).wait_time =
        charge_station(veh_struct.CS).wait_time + ceil((energy_need + 5) * 15 / 200) * 2;
    end
end

case 2 % CS has been assigned, moving to CS and reassign CS if better CS exists

new_CS = assign_CS(veh_struct,charge_station);
if new_CS ~= veh_struct.CS

    % remove from demand queue of old CS
    temp = find(charge_station(veh_struct.CS).demand_queue==veh_struct.ID);
    charge_station(veh_struct.CS).demand_queue(temp) = [];
    charge_station(veh_struct.CS).eta(temp) = [];

    % add to demand queue of new CS
    veh_struct.CS = new_CS;
    t2c = ceil((sum(abs(veh.des - charge_station(veh_struct.CS).coord)+
                 abs(veh.current - charge_station(veh_struct.CS).coord)) - veh.SOC) * 15 / 200) * 2;
    temp_time = sum(abs(charge_station(veh_struct.CS).coord-veh_struct.current));
    % sorted by eta
    temp_queue = sortrows([add_queue(temp_time,charge_station(veh_struct.CS).eta)',
                            add_queue(veh_struct.ID,charge_station(veh_struct.CS).demand_queue)',
                            add_queue(t2c,charge_station(veh_struct.CS).t2c')]');
    charge_station(veh_struct.CS).eta = temp_queue(:,1)';
    charge_station(veh_struct.CS).demand_queue = temp_queue(:,2)';
    charge_station(veh_struct.CS).t2c = temp_queue(:,3)';

end

if sum(abs(veh_struct.current-charge_station(veh_struct.CS).coord))~=0

    veh_struct.current = move_veh(veh_struct.current,
          charge_station(veh_struct.CS).coord);
    veh_struct.SOC = veh_struct.SOC - 1;
    temp = charge_station(veh_struct.CS).eta(charge_station(veh_struct.CS).demand_queue==veh_struct.ID) - 2;

    charge_station(veh_struct.CS).eta(charge_station(veh_struct.CS).demand_queue==veh_struct.ID) = temp;

else % already at the CS
if isempty(charge_station(veh_struct.CS).actual_queue) &&
charge_station(veh_struct.CS).charging==0 % can start charging in next second

    veh_struct.status = 4;
    charge_station(veh_struct.CS).charging = veh_struct.ID;
    charge_station(veh_struct.CS).wait_time = ceil((energy_need + 5) * 15 / 200) * 2;

else

    veh_struct.status = 3;
    charge_station(veh_struct.CS).actual_queue =
    add_queue(veh_struct.ID,charge_station(veh_struct.CS).actual_queue); % add vehicle to
    actual queue
    veh_struct.TIQ = veh_struct.TIQ + 2;
    charge_station(veh_struct.CS).wait_time =
    charge_station(veh_struct.CS).wait_time + ceil((energy_need + 5) * 15 / 200) * 2;

end

end

case 3 % wait in queue

    if charge_station(veh_struct.CS).charging== 0 &&
    charge_station(veh_struct.CS).actual_queue(1)==veh_struct.ID % if there is an empty
    spot and first of the queue

        veh_struct.status = 4;
        charge_station(veh_struct.CS).actual_queue(1)=[]; %remove from the actual
    queue
        charge_station(veh_struct.CS).charging = veh_struct.ID; % start charging in
    next second

    else

        veh_struct.TIQ = veh_struct.TIQ + 2;

    end

case 4 % charging

    if veh_struct.SOC - energy_need >=5 % enough SOC to finish the trip (5 miles
    clearance)
veh_struct.status = 0;
charge_station(veh_struct.CS).charging = 0; %remove from charging
charge_station(veh_struct.CS).demand_queue(charge_station(veh_struct.CS).demand_queue==veh_struct.ID)=[]; %remove from demand queue
charge_station(veh_struct.CS).eta(charge_station(veh_struct.CS).demand_queue==veh_struct.ID)=[];
charge_station(veh_struct.CS).t2c(charge_station(veh_struct.CS).demand_queue==veh_struct.ID)=[];

% start moving to des
veh_struct.current = move_veh(veh_struct.current, veh_struct.des);
veh_struct.SOC = veh_struct.SOC - 1;

else % charging
    veh_struct.SOC = veh_struct.SOC + 100/7.5;
    charge_station(veh_struct.CS).output_p = charge_station(veh_struct.CS).output_p + 100/7.5;
    charge_station(veh_struct.CS).wait_time = charge_station(veh_struct.CS).wait_time - 2;
    temp = charge_station(veh_struct.CS).t2c(charge_station(veh_struct.CS).demand_queue==veh_struct.ID) - 2;

charge_station(veh_struct.CS).t2c(charge_station(veh_struct.CS).demand_queue==veh_struct.ID) = temp;

end

otherwise
'error'
end

veh_struct.TTTwc = veh_struct.TTTwc + 2;
end
end
function [current] = move_veh(current, des)
% des and current are in [x y] format
temp = des - current;

if temp(1)~=0 && temp(2)==0
    if rand <=0.5  %randomly move on x or y direction
        current = current + sign(temp(1))*[1 0];
    else
        current = current + sign(temp(2))*[0 1];
    end
else  % temp(1)==0 or temp(2)==0
    current = current + sign(temp(1))*[1 0] + sign(temp(2))*[0 1];
end
end

function [queue]=add_queue(ID,queue)
% add a veh to queue
if ~isempty(queue)
    queue = [queue ID];
else
    queue = ID;
end
end

function [ID] = assign_CS(veh, charge_station)
% return the ID of best charging station
range = veh.SOC;
min_cost = inf;

for i = 1:length(charge_station)
    dis = sum(abs(veh.current - charge_station(i).coord));
    if dis <= range
        eta = dis * 2;  % time to station
        pointer = find(charge_station(i).eta <= eta, 1, 'last');
        if isempty(pointer)
% no vehicle in queue when arrive
et_CS = ceil((sum(abs(veh.des - charge_station(i).coord) + abs(veh.current - charge_station(i).coord)) - veh.SOC) * 15 / 200) * 2; % time in the charging station
else
    et_CS = charge_station(i).eta(1) + charge_station(i).t2c(1);
    for j = 2 : pointer
        if charge_station(i).eta(j) < et_CS
            et_CS = et_CS + charge_station(i).t2c(j); % time in the charging station
        else
            et_CS = charge_station(i).eta(j) + charge_station(i).t2c(j);
        end
    end
end
if eta < et_CS
    et_CS = et_CS + t2c;
else
    et_CS = eta + t2c;
end

cost_t = eta + et_CS + sum(abs(veh.des - charge_station(i).coord)) * 2;
if cost_t < min_cost
    min_cost = cost_t;
    ID = charge_station(i).ID;
elseif cost_t == min_cost && rand > 0.5 % in case there are more than one best solution, 50% replace selection
    min_cost = cost_t;
    ID = charge_station(i).ID;
end
end
end
end
function [ charging_station ] = updateCS( charging_station,t)

% UPDATECS use to update charging_station list

for i = 1:length(charging_station)
    charging_station(i).demand_t(t) = length(charging_station(i).demand_queue);
    charging_station(i).actual_t(t) = length(charging_station(i).actual_queue);
end

end
Test function for Case 0 (test_a0)

function test_a0(grid_size,num_veh)

load(['CS_base_', num2str(grid_size)])
load(['veh_base_', num2str(grid_size)])

t_total = num_veh;
t = 1;
t_step = 0;
veh_moving = [1 2];
veh = veh(1:num_veh);

while ~isempty(veh_moving)
    for veh_n = veh_moving
        [veh(veh_n),charging_station] = vehicle0(veh(veh_n), charging_station);

        if sum(abs(veh(veh_n).current - veh(veh_n).des))==0
            veh_moving(veh_moving==veh_n)=[];
        end
    end
    if t < t_total - 2
        veh_moving = [veh_moving (t+2) (t+3)];
    end

    t_step = t_step + 1;
    [ charging_station ] = updateCS( charging_station , t_step);
    t = t + 2;
end

for i = 1:length(charging_station)
    charging_station(i).demand_t = charging_station(i).demand_t(1:t_step);
    charging_station(i).actual_t = charging_station(i).actual_t(1:t_step);
end

save(['test_a0_',num2str(grid_size),'_','veh',
'charging_station','t_step'])
end
Test function for Case 1 (test_a1)

function test_a1(grid_size,num_veh)

load(['CS_base_', num2str(grid_size)])
load(['veh_base_', num2str(grid_size)])

% Initialize simulation parameters

t_total = num_veh;
t = 1;
t_step = 0;
veh_moving = [1 2];
veh = veh(1:num_veh);

while ~isempty(veh_moving)

    for veh_n = veh_moving
        [veh(veh_n),charging_station] = vehicle1(veh(veh_n), charging_station);
    
        if sum(abs(veh(veh_n).current - veh(veh_n).des))==0
            veh_moving(veh_moving==veh_n)=[];
        end
    
    end

    if t < t_total - 2
        veh_moving = [veh_moving (t+2) (t+3)];
    end

    t_step = t_step + 1;
    [ charging_station ] = updateCS( charging_station , t );
    t = t + 2;
end

for i = 1:length(charging_station)
    charging_station(i).demand_t = charging_station(i).demand_t(1:t_step);
    charging_station(i).actual_t = charging_station(i).actual_t(1:t_step);
end

save(['test_a1_',num2str(grid_size),'_',num2str(num_veh)], 'veh',
'charging_station','t_step')
end
Test function for Case 2 (test_a2)

function test_a2(grid_size,num_veh)

load(['CS_base_', num2str(grid_size)])
load(['veh_base_', num2str(grid_size)])

t_total = num_veh;
t = 1;
t_step = 0;
veh_moving = [1 2];
veh = veh(1:num_veh);

while ~isempty(veh_moving)
    for veh_n = veh_moving
        [veh(veh_n),charging_station] = vehicle2(veh(veh_n), charging_station);
        if sum(abs(veh(veh_n).current - veh(veh_n).des)) == 0
            veh_moving(veh_moving==veh_n)=[];
        end
    end

    if t < t_total - 2
        veh_moving = [veh_moving (t+2) (t+3)];
    end

    t_step = t_step + 1;
    [ charging_station ] = updateCS( charging_station , t );
    t = t + 2;
end

for i = 1:length(charging_station)
    charging_station(i).demand_t = charging_station(i).demand_t(1:t_step);
    charging_station(i).actual_t = charging_station(i).actual_t(1:t_step);
end

save([test_a2_ '.' num2str(grid_size) '.' '_' num2str(num_veh)], 'veh', 'charging_station', 't_step')
end
Test function for Case 3 (test_a3)

function test_a3(grid_size,num_veh)

load([CS_base_, num2str(grid_size)])
load([veh_base_, num2str(grid_size)])

t_total = num_veh;
t = 1;
t_step = 0;
veh_moving = [1 2];
veh_nm = [3:num_veh]; % vehicles that have not started
veh = veh(1:num_veh);

while ~isempty(veh_moving)

    % handling vehicles in the network
    for veh_n = veh_moving

        [veh(veh_n).charging_station] = vehicle3(veh(veh_n), charging_station);

        if sum(abs(veh(veh_n).current - veh(veh_n).des))==0
            veh_moving(veh_moving==veh_n)=[];
        end
    end

    % handling vehicles that have not started
    % assign vehicle to demand queue
    n_counter = 1;
    for veh_n = veh_nm

        extra_time = ceil(n_counter / 2) * 2;

        [veh(veh_n).charging_station] = vehicle3_n(veh(veh_n), charging_station, extra_time);

        n_counter = n_counter + 1;
    end

    if t < t_total - 2
        veh_moving = [veh_moving veh_ns(1:2)];
    end

end

end
veh_nm(1:2) =[];

end

t_step = t_step + 1;
[ charging_station ] = updateCS( charging_station , t );
t = t + 2;
end

for i = 1:length(charging_station)
    charging_station(i).demand_t = charging_station(i).demand_t(1:t_step);
    charging_station(i).actual_t = charging_station(i).actual_t(1:t_step);
end

%save([test_a3_,'num2str(grid_size)'_'num2str(num_veh)'], 'veh',
'charging_station','t_step')
end
REFERENCES


