Optimized System for On-Route Charging of Battery Electric Buses and High-Fidelity Modelling and Simulation of In-Motion Wireless Power Transfer

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OPTIMIZED SYSTEM FOR ON-ROUTE CHARGING OF BATTERY ELECTRIC BUSES
AND HIGH-FIDELITY MODELLING AND SIMULATION OF IN-MOTION WIRELESS
POWER TRANSFER

by

Yogesh Bappasaheb Jagdale

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in partial fulfillment of the requirement
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Electrifying cars, buses and trucks is an attractive means to reduce energy use and emissions, because it involves minimal restructuring of the transportation network. Transit buses drive fixed routes, minimizing driver range anxiety by properly sizing energy storage system but the major challenge to fully electrifying transit buses, is the amount of energy they consume in a day of driving. To enable a full day of operation, batteries need to be large, which is expensive and heavy. This work utilizes real-world transit bus data fed to a battery electric drive-train model to co-optimize charger locations, charger power levels, and vehicle battery sizes. The electrification study expands to Dynamic Wireless Power Transfer. When applied, in-motion WPT additionally relieves range anxiety, it reduces battery size consequently increasing fuel economy, and it increases the battery life through charge sustaining approach. In existing research, small-scale infrastructure studies have been achieved but additional research is needed for improved fidelity. The work represents to a novel, large-scale integration of numerous research methodologies into a comprehensive study to thoroughly address potential in-motion WPT usage situations. High fidelity modeling of in-motion WPT will be implemented on hybrid electric and EVs in MATLAB/Simulink & Python. ANL’s Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model is also included in the analysis to accurately compare energy usage for all vehicle architectures. The outcomes of the study show that the transit bus electrification and in-motion charging using WPT presents both economic and environmental advantages when contrasted with ordinary ICE transportation and a long range EV fleet.
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Yogesh Bappasaheb Jagdale
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1. INTRODUCTION

1.1 Need of Electrification

The cost of fuels like petrol, diesel etc. has been steadily increasing due to increased number of vehicles and proportional excess usage of fuel and limited sources of fossil fuel. Depleting sources of these fuels is one of the major concerns. The age-old designs of vehicles are the major contributors to the problem of greenhouse gases. The future of automotive technologies is moving toward electric vehicles which are considered as a replacement to oil-powered internal combustion engine driven vehicles, keeping in mind CO2 reduction. With In- Motion WPT we can replace fossil fuels by electricity as the standard fuel for vehicles at major extent.

Electric vehicles offer a promising alternative to internal-combustion vehicles because they don't burn fossil fuels. They are also capable of producing instant torque and smoother acceleration than conventional cars. A 2018 study from the University of Michigan's Transportation Research Institute found that electric vehicles cost less than half as much to operate as gas-powered cars. The average cost to operate an EV in the United States is $485 per year, while the average for a gasoline-powered vehicle is $1,117. The exact price difference depends on gas and electric rates at place, plus the type of car you drive [1].

Another significant difference between electric vehicles and gasoline-powered vehicles is the number of moving parts. The electric vehicle has fewer moving parts, one of them is the motor, whereas the gasoline-powered vehicle has hundreds of moving parts. Fewer moving parts in the electric vehicle leads to another important difference. The electric vehicle requires less periodic maintenance and is more reliable. The gasoline-powered vehicle requires a wide range of maintenance, from frequent oil changes, filter replacements, periodic tune ups, and exhaust system repairs, to the less frequent component replacement, such as the water pump, fuel pump, alternator, etc. The availability of incentives for buying electric vehicles, coupled with their continuously falling costs, has made an investment in an EV a smart energy and money decision. Electric
vehicles are not for every lifestyle, but when compared to the myriad costs surrounding ICE purchase and maintenance, choosing an EV can be an intelligent fiscal decision [2].

Figure 2: Example of Issues In Current Vehicle Technology And Their Solutions

To address the problems mentioned in Figure 2 and get solution for these problems’ electrification is needed.

1. To reduce the air pollution by vehicles we need to reduce the exhaust gases which emits from vehicles we can achieve that by using electric vehicles since the direct emissions from electric vehicles are zero.
2. For CO2 regulation it needs to follow the Fuel Economy Regulations and for that electric vehicles have massive role to play.
3. As the resources of non-renewable energy sources are depleting, we need to choose renewable energy sources to replace them and electricity can be produced with these sources will have economic as well as environmental benefits.

Electrification of the transportation sector is a significant opportunity to improve urban air quality and decrease global carbon emissions. In transit bus scenario as we cannot generate electricity onboard, we need to use batteries to store energy. The driving range of battery electric buses is limited, and the charging process takes huge amount of time because the energy density of battery is lower as compared to the diesel. The efficiency of converting electric energy to rotational work for Electric motors in electric vehicles is 2.5-3 times than the internal combustion engine which converts diesel to rotational work. Public transit fleets have had many successes as early adopters of parallel hybrid, range extended hybrid, full battery electric, and hydrogen fuel cell drivetrain. Their success can largely be attributed to their daily duty cycles, characterized by the stop-and-go driving that provides numerous opportunities for regenerative braking.
1.2 Transit Bus Electrification

1.2.1 Different Methods for Transit Electric Bus Charging

There are two different methods for charging the transit electric buses one is standard charging and other is fast charging. Standard charging is a charging with moderate charging power usually overnight charging of bus in the in the bus depot or during longer breaks. This requires a higher battery capacity and higher weight of the system, when the bus shall be operated the entire day. Fast charging is a charging which is carried out on-route with the help of overhead chargers or wireless power transfer at terminal stop, bust-stop, in depot. Fast charging on route during operation can reduce battery capacity and furthermore the weight significantly. However, bus schedule must provide enough charging time at certain locations [3].

1.2.2 Calculation Method for Implementation of On-Route the Fast Chargers

The simulation method for calculation and implementation of on route the fast chargers is divided in 3 different steps first step is to calculate Energy Consumption. The first step is to calculate energy consumption of each trip is simulated based on the defined bus type and the geographical characteristics of the bus route. The second step is Vehicle Scheduling and Grid Load profiles. The service trips are combined to individual vehicle schedules based on the determination set of service trips including the available charging time at the terminal stops. After this from every charging station and the entire network, which reveals the impact of simultaneous charging process the resulting power profiles are derived. And the last step is to calculate the Battery Capacity. The required battery capacity is calculated for each bus route based on the given charging power [3].

1.3 Overview of Bus Electrification Project

This work will focus on battery electric buses. Although these buses achieve considerable energy recapture and conversion efficiency, incorporating them into a fleet can be challenging for managers, because their driving range is restricted, and recharging can keep the buses out of operation for considerable periods of time. The battery for electric buses can be charged in two ways; one is standard charging and other is fast charging. In standard charging process overnight charging of the battery occurs at the depot with the help of low to moderate charging power charger. For the whole day operation, it requires a huge battery capacity, and this also increases the weight of the bus.

The on route fast charging helps to reduce the battery capacity and it also results in reducing the weight of the system. For a day operation, a transit bus may require a battery as large as 500 kWh. Compared to energy storage by liquid fuel (for example diesel, 0.832kg/liter), batteries are expensive (300$/kWh) and heavy (10kg/kWh) [4]. As the mass of the bus increases with on-board capacity, the energy consumption also increases, creating a subtle but not negligible positive feedback loop. On-route charging breaks this loop by reducing the need for installed battery capacity, and offsets the significant cost of charging infrastructure by reducing the mass and cost of the vehicles. The purpose of this work is to analyze existing bus networks to identify opportunities for electrification with fast charging battery buses. With the help of fast chargers installed at depot or on route bus stops for charging the battery scheduled stop time. Because of
the cyclic nature of transit bus routes, abound for on-route charging. The analysis is based on real-world data of the bus network in Zion National Park. The data fed to a battery electric drive-train model to co-optimize charger locations, charger power levels, and vehicle battery sizes. Ten different zones are considered as charging opportunities as Zion National Park route has 9 bus stops and a depot. To recognize opportunities for battery electric bus charging along the bus route, a bus route map from the park was consulted, and geofences were drawn around each stop to classify dwell time at each stop. The result is a feasible operating schedule for electric buses driving existing routes and sharing charging infrastructure without exhausting their batteries or interrupting service.

1.4 Overview and Limitations in Current Technology (Stationary Charging) & Need of In-Motion Wireless Power Transfer

From 2023 onward, all taxis in Oslo will be zero emission with electrification. But current vision for most EV’s is stationary charging at charging stations located at homes and offices with wired chargers. The disadvantage of the Stationary Wireless Power Transfer system is it requires long recharging times, and high capital cost. Also, it adds the limitation of the limited range especially, in cold weather battery capacity is reduced. So rather waiting for the perfect battery why not change the charging system? In-motion WPT system is less complex, saves the longer time required for the charging, reduced battery size and hence reduce the cost of the vehicle as well. So, In-motion Wireless Power Transfer (WPT) is an exciting alternative for the stationary charging system.

Figure 3: Future Concept for Dynamic Wireless Power Transfer (DWPT)

As the number of electric vehicles are increasing per year the Dynamic (In-motion) Wireless Power Transfer will be a great option for charging all vehicles with same infrastructure at the same time. It will eliminate the issue of range-anxiety and will save the longer time which is required in the stationary charging. As the graph shown in Figure 4 below suggest that by the
end of 2040 the number of Electric Vehicles will be around 60 million which is significantly more EVs that there are currently. So Dynamic Wireless Power Transfer is the one of the better options for future of electrification.

Figure 4: Increase In Electric Cars Per Year

1.5 Overview of Dynamic Wireless Power Transfer (DWPT) Project

The goal of this research project is to study In-Motion WPT using models and simulations that have higher-fidelity than what is used in the latest publications [5,6] which would progress In-Motion WPT towards widespread implementation. There are numerous aspects of In-Motion WPT that require new analysis such as the impacts of inductive versus capacitive In-Motion WPT, the use of validated high-fidelity vehicle models, the inclusion of more real world drive cycles, design investigations of vehicles used specifically for In-Motion WPT including transition designs, high-fidelity infrastructure rollout scenarios.

Consumer adoption of EVs has been limited due to their restricted range, long recharging times, and higher total purchase price due to their large batteries [7,8]. In-Motion WPT has the potential to improve the range, consumer acceptability, and costs of EVs without requiring the integration of large capacity batteries. This has been the main finding in overall system operation reviews [9-11], technology reviews [12-15], and new reviews published in the last three years [16-21]. Because of the potential benefits of In-Motion WPT, numerous research programs are dedicated to the realization of In-Motion WPT, but they are primarily focused on electrical system design. This project addresses a larger-scope system analysis that includes high-fidelity vehicle models, a large real-world drive cycle database, economic considerations, and environmental impacts. Properly quantifying the relevance of this technology to the vehicle transportation sector can further motivate electrical system technological performance goals.

Talking about contribution to the field based on the current state of the field, there exists the need for higher-fidelity large-scale assessment of the economic potential and sustainability of an In-Motion WPT fleet in the U.S., a scope that has not been adequately addressed by previous research. There is a strong need for large-scale integration of vehicle models, In-Motion WPT models, regional energy and emissions models, and economic models. To enable this new contribution to the field, high-fidelity vehicle models, a large database of real-world drive cycles,
various versions of In-Motion WPT system models, and new economic models are needed. These models will be developed in this project and will be linked to existing energy and emissions models.

This project addresses larger societal issue of transportation sustainability. Transportation accounts for approximately one third of worldwide energy consumption [22]. When this energy is generated from combustion engines, petroleum importing and exporting is required, air pollution is released, and global warming is exacerbated. On a per-country basis, petroleum consumption is often unbalanced from domestic production, creating the issue of energy security and vulnerability to geopolitical stability [22] as evidenced by the 1973-1974 oil embargo on the United States [23]. The greenhouse gas emissions from transportation combustion engines contribute significantly to the increasing global temperature which can severely inhibit animal and human life [24,25]. Transportation combustion engines also contribute to air pollution which is the fourth-leading cause for premature death worldwide [26].

This project provides significant research into the larger societal issue of near-term electrification of long-distance trucking, a transportation sector particularly resistant to efficiency improvements, electrification, and fueling changes [27,28]. Long-term studies found that electrified rail transport may be the only current means to reduce the environmental costs of freight transport [29] but this costs between $4.8-$55 million per track mile to implement in a large geographic area [30,31]. In-Motion WPT of freight transportation systems has the potential to realize the environmental benefits of freight electrification but at a significantly lower cost than electrified rail. Overall, In-Motion WPT is a unique solution to transportation sustainability because it allows vehicles to operate at a much lighter weight, it does not require extensive large battery manufacturing as we can charge vehicle on route and use smaller batteries, and it is easily deployable through current vehicles and road systems.

1.6 Pros/Cons of In-Motion Wireless Power Transfer

In-Motion Wireless Power Transfer has some advantages and limitations, the advantages and the limitations which are discussed in this section.

1.6.1 Pros of In-Motion Wireless Power Transfer

In-Motion Wireless Power Transfer the biggest advantage is battery size gets reduced and as a result of that the cost of Electric Vehicle reduces and solves one of the biggest problems associated with Electric vehicles. Which also results in increasing the efficiency of the system as the weight reduces and so the energy consumption. In Dynamic Wireless Power Transfer the energy efficiency is also increased. And In-Motion Wireless Power Transfer reduces concerns of the biggest problem associated with current electric vehicle technology which is range anxiety. In-Motion wireless power transfer allows extended driving range as the vehicle gets charged while driving. Also, it helps to reduce emissions, and which makes it environmentally friendly technology for electric vehicles.
1.6.2 Cons of In-Motion WPT

The infrastructure associated with In-Motion Wireless power transfer is expensive as it involves a lot of electronics, power transfer from grid to road and other things related to it. And the implementation scope for now is limited to long distance route and urban environment.

![Image Showing Wireless Power Transfer Lane](image)

Figure 5: Image Showing Wireless Power Transfer Lane

1.7 Risks in In-Motion Wireless Power Transfer System

To implement an IM-WPT system some challenges must be observed such as:
1. Synchronization of a track and the pick-up coil
2. Timing of power transfer
3. Misalignment or Vehicle alignment, especially maintenance of lateral alignment
4. Allowable speed profiles and issues with coil ring-up for the segmented track case
5. Multiple charging lanes and their issues
6. Multiple vehicles on charging lane and power flow management
7. Need for low latency, private and secure, bidirectional communications
8. Acceptable power levels vs. vehicle class types and Frequency Variation

Several high-level challenges emerged such as utility power distribution in the roadway, robustness of embedded WPT units and their sequencing, high speed bidirectional communications, construction costs, and impact of highway resurfacing on WPT robustness and efficiency. If we overcome all these problems the system will be smooth to run, very efficient and environment friendly as well [32-34].
1.8 In-Motion WPT Techniques

1.8.1 Inductive Wireless Power Transfer

Inductive Wireless Power Transfer (IPT) uses magnetic field coupling between conducting coils. IPT has high efficiency and high-power capability. Due to large airgap, magnetic coupling is relatively low. It is very effective for short & medium distance to transfer high power. But this IPT configuration is a bulky configuration and a little expensive as well due to electronics in comparison to CPT. It is very effective in high power transfer, but efficiency reduces due to misalignment. Also, one of the disadvantages of this system is that its sensitivity to metal objects.

1.8.2 Capacitive Wireless Power Transfer

Capacitive Wireless Power Transfer (CPT) Uses electric field coupling between conducting plates. One of the advantages of CPT configuration over IPT configuration is that its reduced sensitivity to misalignment. But the biggest problem associated with this system is that it needs a huge area to transfer several kW Power so we cannot transfer high power by using this configuration. Also, due to very small capacitance the effective power transfer occurs at very high frequencies.

![Figure 6: Block Diagram of Inductive and Capacitive Wireless Power Transfer](image)

1.9 Comparison Inductive WPT vs Capacitive WPT

The functioning and working principle for both Inductive Wireless Power Transfer as well as Capacitive Wireless Power Transfer has addressed in the block diagram shown below. In IPT it shows in Figure (7) that the transformer uses magnetic field coupling between conducting coils to transfer the power wirelessly from primary compensation network to the secondary compensation network. Similarly, in Figure (8) it shows how it uses the electric field coupling between the capacitor plates to transfer the power from primary compensation network to secondary compensation network wirelessly.
Figure 7: IPT Configuration Using Magnetic Fields to Transfer Power Through Transformer

Figure 8: CPT Configuration Using Magnetic Fields to Transfer Power Wirelessly Through Capacitor Plates

The table below shows the comparison between Inductive & Capacitive Wireless Power Transfer Technologies by comparing different factors like frequency, power, efficiency, distance, cost and size.

Table 1: Comparison of Inductive and Capacitive Wireless Power Transfer Technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Frequency</th>
<th>Power</th>
<th>Efficiency</th>
<th>Distance</th>
<th>Cost</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductive</td>
<td>kHz-MHz</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>Capacitive</td>
<td>kHz-MHz</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

- **IPT system is a good solution for EV charging**
- **CPT has potential to reduce the system cost**

To transfer high power IPT is best solution right now so studied IPT in details.

### 1.10 GREET Model

ANL’s (Argonne National Laboratory) Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model is also included in the analysis to accurately compare energy usage for all vehicle architectures. GREET calculates the emissions (CO2, CH4, and N2O) that result from transportation life cycles consists of several stages, such as end use, transportation, distribution and production.
GREET consists of two modules:

1. GREET1 evaluates WTW energy use and emissions of vehicle/fuel systems
2. GREET2 evaluates energy use and emissions of vehicle manufacturing cycle

There are four main panes in GREET Software [38]:

1. WTP (Well-to-Pump)
2. WTW (Well-to-Wheels)
3. Data Editors
4. Simulation Parameters

Figure 9: GREET Pane

- Consists of two modules [37]:
  1. GREET1 evaluates WTW energy use and emissions of vehicle/fuel systems
  2. GREET2 evaluates energy use and emissions of vehicle manufacturing cycle

Figure 10: GREET 1 & GREET 2 Cycles [37]
Table 2: GREET Terminologies

<table>
<thead>
<tr>
<th>Process</th>
<th>A process is the major building block in the model. Most of the calculations take place at the process level. Two types of processes in the model stationery and transportation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathways</td>
<td>A pathway is a graph that has processes as nodes and directed edges between processes define the sequence</td>
</tr>
<tr>
<td>WTP</td>
<td>3 zones, 1-products zone 2-results associated with selected pathway 3-pathway or pathway mix</td>
</tr>
<tr>
<td>WTW</td>
<td>2 zones, 1-vehicles to be selected categorized by fuel used 2-results of vehicle selected</td>
</tr>
<tr>
<td>Data Editors</td>
<td>The resource editor allows you to add new resources or edit existing ones</td>
</tr>
<tr>
<td>Simulation Parameters</td>
<td>The Simulation Parameters main pane contains parameters that are reused in many places though the model</td>
</tr>
</tbody>
</table>
1.11 Literature Review

To promote green mobility Electric vehicles (EVs) have been evolved as promising technology in last few years. Less energy consumption compared to the thermal vehicles is the most important advantage of EVs. Limited sources of fossil fuels are also a major concern and EVs can be good alternative as the electric energy to charge batteries can be generated from renewable energy sources and it is beneficial to the environment as well. However, despite such advantages and the involvement from industry, subsidy from government and tax incentives, EVs have not yet become an attractive solution to consumers in general. The problem is due to some limitations which still need to be solved regarding the electricity storage technology (i.e. battery); due to its unacceptable energy density, limited lifetime, long charging time and high cost [16].

To overcome these problems wireless power transfer is one of the solutions. Wireless power transfer plays a vital role in charging electrical vehicles (EVs), for that different wireless power charger structures for EVs have been projected. Compared to the wired charging, WPTC offers advantages like; no exposed wires, ease of charging, transmission of power in adverse environmental conditions [16]. Stationary wireless charging in which the electric vehicles (EVs) should be in static condition for long time which is not a convenient way. But to reduce the battery size to store the electricity and therefore improving the efficiency dynamic (In-motion) wireless power transfer is more convenient option for charging of EVs. Smaller size and cheaper battery achieving a long driving range without any waste of time at a charging station is obtained due to the ability to charge the battery while the EV is in motion [39].

In motion WPT does not required bulky contacts, wires, plugs and does not get affected by adverse environmental conditions. When applied, in-motion WPT additionally relives range anxiety, it reduces battery size consequently increasing fuel economy, and it increases the battery life through charge sustaining approach. The power transfer capacity, efficiency, lateral tolerance, electromagnetic field, airgap, size, weight and cost of the WPTSs can be improved by virtues of innovative semiconductor switches, better coil designs, roadway construction techniques, optimized compensation networks and higher operating frequency [39].

There are lot of research papers available which addresses aspects of Dynamic Wireless Power Transfer such as vehicle modelling, Wireless Power transfer modelling, environmental analysis, cost estimation but it is rare that research paper talk about all these aspects together. A lot of articles talk about primary research in wireless power transfer and general calculation of it. These articles also explain about the basics of how Wireless Power Transfer works and the models for wireless power transfer using different software (e. g. MATLAB/Simulink, FEA) [16], [40-43]. Some researchers have analyzed benefits of dynamic charging with an economic model of battery size and charging infrastructure allocation, using a mathematical optimization model of the wireless power transfer technology [44,45]. A paper form ORNL introduces the many challenges facing regarding Wireless Power Transfer in Electric Vehicles is not only high-power transfer to a moving vehicle and energy management at a utility scale, but communications in a vehicle to infrastructure (V2I) environment and management of high data rates, ultra-low latency, and dealing with communications loss in dense urban areas [46].

In a literature named ‘Advances in Wireless Power Transfer Systems for Roadway-Powered Electric Vehicles’, the development history of Inductive Power Transfer System (IPTS) for Roadway Powered Electric Vehicles (RPEV) from its advent to its current status as a state-of-the-art
technology has been introduced [47]. A paper by Aqueel Ahmad, Mohammad Saad Alam contains the review of the current status of WPT technologies, development, and applications in transportation. The challenges and opportunities, in terms of technologies and sustainability performance, have been discussed [48]. Some researchers in their paper explain about the primary research and analysis of the wireless power transfer system. It includes methods for analyzing the performance of different wireless power transfer techniques such as Inductive Wireless Power Transfer, Capacitive Wireless Power Transfer, Resonant-Coupling, etc. while driving the electric vehicles and the infrastructure associated with the whole system, increasing output power to secondary side to increase the efficiency of dynamic wireless power transfer system [16], [49-57].

Novel optimization procedure in order to maximize the energy transferred to an EV, at considerably high efficiency by a dynamic IPT system is proposed by Ioannis Karakitsios, Foivos Palaiogiannis, Achilleas Markou [58]. Hong Kong College of technology has primarily researched on Some things like Road planning, Safety issues, Battery Standardization. This paper looks at researching and developing a mass and flexible dynamic battery recharging system. voltage fluctuation is one of the problems that is seen while WPT using high-frequency resonant operation theories and a special shape coil to overcome this. Thomas Navidi, Yue Cao has worked on the efficiency, energy transfer, and feasibility analysis on a proposed WPT system and a catenary system for electric vehicle charging on rural highways by using the average modeling in MATLAB/Simulink [59]. Thammasat University Rangsit Campus studied a new method for implementing, modeling, and measuring in-motion WPT for an EV charger. Increase understanding of implementation, characteristics, operation, communication, and control of in-motion WPT by using MATLAB/Simulink using low-cost hardware such as Arduino to implement a testbed system. Also, has explained Economic model (EM) for dynamic charging EV with consideration of the battery life. It also explains the Dynamic wireless charging system is beneficial to both the reduction of the battery size and extension of battery life [60].

Nikolay Madjarov, Aitor Bustillo has worked on A complete and new inductive charging system is developed which consists of the module that is capable of transfer of 30KW for 9 cm air gap. New positioning mechanism and worked on Cost-benefit analysis are also done [61]. The need and development in wireless power transfer and Electric vehicles are reviewed in this paper. The progress in the Mid-range stationary wireless power transfer is discussed and adopted for further research and its implementation. The RIPT Simulation is designed at MATLAB with an efficiency of 85%. The maximum energy efficiency approach is used with two coil resonators showing the application of charging EV desirable for Stationary WPT [62]. A paper from Siqi Li; Chunting Chris Mi in reviewed the technologies in the WPT area applicable to EV wireless charging. By introducing WPT in EVs, the obstacles of charging time, range, and cost can be easily mitigated. Battery technology is no longer relevant in the mass market penetration of EVs. It is hoped that researchers could be encouraged by the state-of-the-art achievements and push forward the further development of WPT as well as the expansion of EV [63].

Oak Ridge National Laboratory has worked and published an article which explains An Evanescent Power Transfer (EPT) demonstration system has been designed, fabricated, and tested to statically and wirelessly transfer power to charge EVs and to measure its performance parameters. The goal was to determine how wireless power transfer could be applied to the wireless charging of vehicles. Transfer efficiency is the power delivered to the load divided by the input power supplied to the transmitting antenna multiplied by 100. The maximum power transferred measured in the lab was 4.2 kW with 92% transfer efficiency [64]. In 2017, Ahmed A. S.
Mohamed; Christopher R. Lashway; Osama Mohammed published an article about a new bi-directional wireless power transfer (BWPT) charging and discharging concept that is analyzed for its feasibility in integration at traffic signals. Classified as quasi-dynamic WPT (QDWPT), a string of coils is proposed to be installed beneath the road surface to provide grid-to-vehicle (G2V) and vehicle-to-grid (V2G) services to battery electric vehicles (BEVs) while stopped [65].

A study from 2018 literature Economic Viability and Environmental Impact of In-Motion Wireless Power Transfer study has sought to understand the economic and environmental costs and benefits of an in-motion WPT based automotive transportation system. Vehicle energy consumption was modeled over real-world drive cycles under a set of scenarios of vehicle adoption, infrastructure deployment rates, in-motion WPT, and vehicle technologies [66]. With all this some papers are available which tells us more about the potential to revolutionize the road transportation by using these dynamic wireless power transfer and explains details and compares of these different technologies [67-71]. The paper from Idaho National Laboratory has mentioned about the Considerations for Corridor and Community DC Fast Charging Complex System Design and cost estimation [72].

1.12 Novel Contribution

This research is novel because it improves the understanding of environmental, economic, and implementation potential of In-Motion WPT using validated high-fidelity models which have been absent from existing studies. In general, numerous research programs are dedicated to the realization of in-motion WPT by focusing on specific details such as drivable ranges [73], energy transmission efficiency [74,75], weather considerations [76], electrical system design [77-82], physical vehicle implementation [83-85], infrastructure implications [86-89], and traffic implications [90-93]. Most of these studies use rigorous applications of electrical engineering principles to study their limited scope. Few researchers utilize mechanical engineering concepts to study integration with the vehicle and even fewer utilize systems engineering to investigate environmental and economic considerations of In-Motion WPT. From the limited existing studies that include a mechanical engineering and/or systems engineering scope, major findings demonstrate that In-Motion WPT buses may result in an 80% reduction in fuel costs when compared to diesel buses [94], that In-Motion WPT can realize significant decreases in greenhouse gas and air pollution emissions compared to traditional transportation systems [95,96], and initial models show a national return on investment (ROI) of between 5-12 years [1,96-99]. There are no studies that address the environmental, economic, and implementation potential of In-Motion WPT using validated high-fidelity vehicle models. This proposed novel research fills this gap.

This proposed research gives answer to the question When In-Motion WPT is deployed, what are the economic and environmental impacts? Very few researches have all these things combined in one study, it answers that as well. Some studies have the Wireless power transfer model and the results, but we will do it with other important aspects of these studies. It combines the In-motion Wireless Power Transfer study by incorporating it with the vehicle model and doing the economic and environmental analysis of the whole system to study its impact commercially as well as environmentally.
2. OPTIMIZED SYSTEM FOR ON-ROUTE FAST CHARGING OF BATTERY ELECTRIC SHUTTLE BUSES

2.1 Methodology

2.1.1 In-Use Data

NREL’s Fleet DNA Database is an important resource for OEMs, policy makers, and fleet managers [100]. Over 11 million miles of in-use commercial vehicle operations, including the dataset used in this work are available by request. FleetDNA was assembled from a various source: Data loggers installed by NREL engineers to record J1939 CAN communications, and direct partnerships with OEMs or fleets to provide data from existing onboard telematics. The data presented in this work was logged from buses operating in Zion National Park. The buses are Class 8 Navistar Eldorado National models operating on a single restricted access road, within the bounds of the park. The engines burn propane but are otherwise conventional. The national parks service is exploring the possibility of replacing existing buses with Battery Electric Buses, like the 40’ Proterra Catalyst shown in Figure 11. Fortunately, FleetDNA houses in-use data from BEBs operated by Foothill transit in Pomona, CA. Foothill transit has successfully integrated BEBs and on-route fast charging into their operations, making their data especially valuable for comparison to any proposed battery-electric system. Foothill Transit operates Buses with 88kWh and 106 kWh batteries, by charging the buses at 220 kW for 10 5-minute periods throughout the day [101,102].

Two different routes have been used in this study and the data used is from the Fleet DNA. The two routes are:

A. Route 291 (Data used for model calibration)
B. Zion National Park Route

This analysis to study optimized system for on-route fast charging of battery electric shuttle buses occurs in following steps:

1. Create Drivetrain Model (Backward Looking)
2. Tune and Validate Model with Foothill Transit data
3. Run model on data logged from Zion National Park to estimate energy consumption
4. Electric bus energy consumption is simulated using a BEB drivetrain model. Vehicle speed and road grade logged at 1Hz for conventional buses is provided as input to the model.
5. Logged geospatial data is used to estimate charging opportunities for each bus and each stop along the route. Aggregating energy use and charging opportunity into 5-minute bins provides a schedule for the fleet.
6. Vehicle schedules describing dwell times in each zone, and energy consumed driving between them, optimize fleet and charging infrastructure design with Linear Programming to get determine the right number and size of chargers in each zone, as well as the battery capacity of each bus.
2.1.2 Vehicle drivetrain Model

A backward-looking vehicle drivetrain model was used to estimate energy consumption for each bus. The model first calculates the road load on the vehicle:

$$ F_{road} = m \frac{dv}{dt} + mg \sin \theta + C_{dl} v^2 + mg C_{rr} $$

(1)

The model proceeds backward through the driveline, using the radius of the wheel to convert force and vehicle speed to torque and rotational speed. Torque and speed are divided and multiplied by gear ratios of the differential and transmission before an engine torque and speed are used to obtain the motor efficiency from a map. Further details of the model are given in [104,105]. Model parameters are listed in the Table 3. We tried different combinations of mass, drag coefficient, and rolling resistance coefficient to calibrate the electric drivetrain model and get the best possible result out of the different combinations we tried which are shown in detail in next section.

2.1.3 Assumptions to Remove Charging Points

As the data from Foothill Transit has charging events as the route already existing On-Route Fast Charger. Figure 11 shows the bus and the charger at Foothill Transit line 291 and shown the energy consumption with charging events for an entire day’s operation.

Figure 11: Foothill Line 291 Bus and On-Route Charger
Figure 12: Energy Consumption with On-Route Fast Charging

1. Foothill Transit line 291 has a fast charger. Logged data includes mid-day charging events at the Pomona Transit Center.
2. Charging events are characterized by current greater than 350A flowing into the battery.
3. To remove fast-charging events, only data where current is less than 350A is used to calculate net energy consumption.

Figure 13-16 shows the drivetrain model simulation results for the Battery Electric Bus without On-Route Charging.

Figure 13: Logged Speed Vs Modeled Speed and Battery SOC Foothill Transit
Figure 14: Logged Speed vs Modeled Speed SOC Foothill Transit (Small Section)

Figure 15: Modeled Energy Consumption vs Measured Energy Consumption

Figure 16: Distance Traveled in One Day for One Bus
2.1.4 Assumptions for Dataset for Model Calibration

We have selected 10 vehicle days common to all 11 buses in the dataset. Energy use was modeled for the selected days. Modeled energy consumption was compared to measured energy consumption.

Energy consumption for all 11 buses on two of the days out of 10 common days is shown in the figure 17 and figure 18.

![Figure 17: One Day Energy Consumption for One of The Common Days](image1)

![Figure 18: One Day Energy Consumption for 2nd Common Day](image2)
2.1.5 Models with Different Mass and Drag Coefficient for Accuracy

After comparing Modeled vs measured Energy Consumption, it was not as expected. Then we thought to change some parameters to get the accurate results. Checked the model with different mass and different drag coefficients. Some of those results are plotted and shown in Figure 19, 20, 21, and 22. The parameters are chosen which gave the best results.

Figure 19: Modeled vs Measured Energy Consumption Mass = 12000, Drag = 1.617

Figure 20: Modeled vs Measured Energy Consumption Mass = 13000, Drag = 1.617
The figure above and below shows different cases for mass and drag coefficients from that we will choose with what exact parameters the modeled energy consumption matches with the measured energy consumption and if not then we can change mass or drag accordingly.
2.1.6 Energy Consumption Calculation (Parameters Check) & Results

Current events which are less than 350 A are considered (i.e. $I < 350\, \text{A}$) to eliminate the charging events and calculate the net driving energy. After that calculated Modeled vs Measured Energy Consumption for these parameters. As the model is underpredicting we plotted the Avg Speed, Avg Acceleration & Average Absolute Grade to check which parameters we can change. We can increase the mass to get better prediction. As acceleration is dependent on mass & Speed is dependent on drag coefficient. From the above results the parameters are chosen which gave the best result.

![Figure 23: % Deviation for Modeled Vs Measured Energy Consumption](image)

![Figure 24: Model vs Measured Energy Consumption for Average Speed [m/sec]](image)
After considering these parameters which are explained in the figures above shows the model was underpredicting a little bit so we increased the mass to get better prediction results as acceleration is dependent of mass.
2.1.7 Auxiliary Power Calculation

From the Fleet DNA Data, we calculated the Auxiliary Power to get the accurate energy consumption. We calculated the motor energy and the battery energy and from those parameters we can calculate the auxiliary energy use.

\[
\text{Auxiliary Power} = \frac{(\text{Battery Power}) - (\text{Motor Power Electrical})}{\text{Total Duration}} \approx 2kW
\] (2)

2.1.8 Energy Consumption with Auxiliary Loads

To get the more accurate measured consumption that matches with the measured consumption we already have calculated the auxiliary energy consumption with the data from Foothill transit in Pomona city in California.

And then auxiliary energy consumption was added to traction energy consumption to get the total energy consumed by each bus on each day.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>Mass</td>
<td>12500 kg</td>
</tr>
<tr>
<td>C_{dl}</td>
<td>Drag Coefficient</td>
<td>1.617 Ns/m^2</td>
</tr>
<tr>
<td>C_{rr}</td>
<td>Rolling Resistance Coefficient</td>
<td>0.006 N/N</td>
</tr>
<tr>
<td>P_{aux}</td>
<td>HVAC and Auxiliary Load</td>
<td>2 kW</td>
</tr>
</tbody>
</table>

Table 3: Parameters for Vehicle Drivetrain Model

Final Modeled vs Measured Energy Consumption with chosen parameters and adding Auxiliary Energy Consumption is shown in the figure (28).
2.1.9 Model Calibration Results

Those selected 10 common days for 11 buses after removing charging data and adding auxiliary energy consumption we get these results. The modeled consumption agrees with the measured results. But if we consider vehicles with daily energy consumption more than 40 kWh as we can get the results for buses which are running for more time in a day’s operation. Results suggested out of 80 vehicle days 76 are within 15% deviation. The average error in simulated vs logged energy consumption is 11.06 kWh.

Table 4: Model Calibration Results

<table>
<thead>
<tr>
<th>Deviation % (Within)</th>
<th>Number of Days (Total 110 Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>34</td>
</tr>
<tr>
<td>10</td>
<td>64</td>
</tr>
<tr>
<td>15</td>
<td>78</td>
</tr>
<tr>
<td>20</td>
<td>81</td>
</tr>
<tr>
<td>25</td>
<td>83</td>
</tr>
</tbody>
</table>

To calibrate the Battery Electric Bus Model, simulated energy consumption was compared to daily energy consumption measured by foothill transit. Logged data includes mid-day charging events at the Pomona Transit Center. These charging events were removed from the logged dataset so that the drivetrain model could be calibrated without modeling the charging infrastructure.
After comparing modeled and measured energy consumption, model parameters were adjusted to improve agreement. This iterative process of adjusting model parameters and checking energy consumption against measured results was repeated by changing mass, drag coefficient and rolling resistance until the agreement shown in Fig shown below was achieved with the parameter set shown in Table 3.

We then plotted the results and checked for different parameters such as the average velocity, average acceleration, average absolute grade. And the modeled vs measured results are very much like each other as mentioned in the figures (29), (30), (31), (32) which are shown below.

Figure 29: Deviation for Modeled vs Measured Energy Consumption

Figure 30: Model vs Measured Energy Consumption for Average Speed [m/sec]
Figure 31: Model vs Measured Energy Consumption for Average Acceleration [m/sec^2]

Figure 32: Model vs Measured Energy Consumption for Average Absolute Grade
2.1.10 Zion National Part Route and Zones

After estimating energy consumptions from the bus data from Zion National Park to identify opportunities for electric vehicle charging along the bus route, a bus map from the park was consulted, and is shown in Figure 33.

![Zion National Park Route and Zones](image)

Figure 33: Zion National Park Route and Zones

The geofences were drawn around each stop to classify dwell time as shown in Figure 33. Zion National Park has 9 different bus stops and a depot, so we have considered these as 10 different zones for charging opportunities on route. Zone 10 is the bus depot. Figure 34 below shows Stopped time in each zone for one day. 9 bus stops along this route and a depot marked as 10 different zones. Geofences were drawn around the zones. Figure 34 shows 10 different zones in 10 different colors. Zone 10 is bus depot which is shown in blue.
2.1.11 Optimization with Mixed-Integer Linear Programming

To find an optimal charging strategy, a technique known as Mixed-Integer Linear Programming is used to find an optimal number of chargers for the fleet depot, and to find an optimal set of vehicle battery sizes to minimize capital costs while replacing multiple vehicles with their electrical equivalents. My supervisor Eric Miller at NREL helped me understanding this concept and then we worked together on this. A major part of this optimization is done by him.

The method has these objectives:

- **Scheduling**: the solver’s crucial objective is to find a feasible, if not optimal, solution. A feasible solution is a charging schedule that proves each vehicle is able to continue to meet its operational mandate without exhausting its battery or leaving the depot behind schedule.
- **Battery and charger costs**: The solver should account for the capital cost of larger batteries or more/higher power chargers. These costs should be tied to commercially available batteries and charging equipment where available.
- **Personnel availability**: The solver should know that a switch cannot be made at a time when no one is onsite to move buses between the chargers and the parking lot. It’s assumed that vehicles can charge without supervision.
- **Shuttling**: The solver should prefer long blocks of continuous charging in the bus depot. Less time spent moving vehicles back and forth from chargers means less time charging and higher labor costs [104,106].

The problem statement is formulated as:

\[ \text{minimize} \]
\[
\psi = \sum_i (1 - X_i) \psi_f \sum_j \dot{V}_{f,ij} + \sum_i X_i \Delta C \sum_j \psi_{e,j} Y_{i,j} + \psi_b \sum_i C_{battery,i} + \psi_c N_c + \psi_c \sum_{i,j} Z_{i,j} \]

The vehicle schedule is aggregated from logged and modelled timeseries data. Subject to the constraints that:

Each vehicle can be electric (1) or not electric (0):

\[X \in \{0, 1\}\]  \hspace{1cm} (4)

Each vehicle at each time can be charging (1) or not charging (0):

\[Y \in \{0, 1\}\]  \hspace{1cm} (5)

Each vehicle at each time can be plugged in (1) or remain in its current state (0), or be unplugged (0):

\[Z \in \{0, 1\}\]  \hspace{1cm} (6)

Each vehicle at each time should have available battery energy greater than or equal to 0.

\[C_{b,j} + \Delta C \sum_{j=1:k} Y_{y,j} - \sum_{j=1:k} E_{b,ij} \geq 0 \text{ for } k = 1:m\]  \hspace{1cm} (7)

No vehicle, at any time, should charge above its available battery capacity.

\[\Delta C \sum_{j=1:k} Y_{y,j} - \sum_{j=1:k} E_{b,ij} \leq 0 \text{ for } k = 1:m\]  \hspace{1cm} (8)

The number of vehicles that can charge at one time is limited to the number of chargers installed.

\[\sum_i Y_{i,j} \leq N_c \text{ for } j = 1:m\]  \hspace{1cm} (9)

The definition of a switch is that the vehicle was unplugged and is now connected to a charger.
\[ Z_{i,j} \geq Y_{i,j} - Y_{i,j-1} \quad \text{for} \quad j = 2:m \quad (10) \]

Vehicles can only be switched at a time when personnel are onsite.

\[ Z_{i,j} \geq P_j \quad (11) \]

The known inputs to the problem are the time series: energy use, availability for charging, and personnel onsite. The objective function and constraints were programmed using the pyomo toolkit from Sandia National Labs. pyomo provides a compact way to express the logic of the MILP problem, which it then writes to an expanded form which can be read by 3rd party solvers such as Gurobi and COIN, which can be called from pyomo to solve the LP and return results as python variables. pyomo sped iterative development of the algorithm by allowing users to execute each step of this multistep process inside the same jupyter notebook.

2.1.12 Cost Estimation

Cost estimation model contains the infrastructure cost as well as the electric bus cost and calculated the payback period for the whole system.

Charging Station Cost

- Average charging station and charger cost is calculated for two different scenarios the first is to replace 7 buses and second is to replace all 17 buses by their electrical equivalent
- Infrastructure cost is included in total cost

Other Cost Calculation

- Also, Electric bus cost with different battery size must consider
- Total operational cost and maintenance cost also calculated

Payback Period

- Total Cost (Infrastructure + Vehicle purchase) and total cost saving is calculated to get the payback period

2.1.13 Emissions & Energy Use Calculation by using GREET

ANL’s Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model is used to calculate the emissions for different fuel technologies and compare it with electric bus emissions results. The outputs from GREET Model are GHG emissions (CO$_2$, CH$_4$, N$_2$O, and total CO$_{2e}$), Energy use (total, fossil petroleum, coal, natural and renewable energy), Emissions of criteria pollutants (VOC, CO, NO$_x$, PM$_{10}$, PM$_{2.5}$ and SO$_x$); separated into total and urban emissions.
2.2 Results

2.2.1 Vehicle Modelling & Optimization

Two different scenarios have been studied. The first scenario is to replace 7 buses and in the second scenario is to replace all 17 propane buses running in Zion National Park by their electrical equivalent. Two different scenarios have been studied to find an optimal number of chargers for the fleet depot, and to find an optimal set of vehicle battery sizes to minimize capital costs while replacing vehicles with their electrical equivalents.

Table 5 (Scenario 1 and 2): Results for Battery Size and Charger Size With Location

<table>
<thead>
<tr>
<th>Number of Buses</th>
<th>Number of Days</th>
<th>Battery Size (kWh)</th>
<th>Charger Size (kW) &amp; Location (Zone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 (Scenario 1)</td>
<td>7</td>
<td>100 for 1 bus, 125 for 1 bus, 25 for rest buses</td>
<td>75 at zone 5 (Zion Lodge), 75 at zone 9 (Temple of Sinawava), 50 at zone 10 (Bus Depot)</td>
</tr>
<tr>
<td>17 (Scenario 2)</td>
<td>5</td>
<td>25 for each bus</td>
<td>2 Chargers of 75 at zone 4 (Court of Patriarchs), 2 Chargers of 25 at zone 9 (Temple of Sinawava)</td>
</tr>
</tbody>
</table>

Scenario 1:

For 7 transit buses and 7 days of operation, the optimization routine returns a result of 3 chargers, 75 kW at zone 5 (Zion Lodge), 75 kW at zone 9 (Temple of Sinawava), 50 kW at zone 10 (Bus Depot) and battery sizes of 100 kWh for one bus, 125 kWh for one bus and 25 kWh for remaining 5 buses. State of Charge profiles in terms of energy consumption for each vehicle are shown in figure (35).
**Scenario 2:**

For 17 transit buses and 5 days of operation, the optimization routine returns a result of 4 chargers, 2 chargers of 75 kW at zone 4 (Court of the Patriarchs), 2 chargers of 25 kW at zone 9 (Temple of Sinawava), and battery sizes of 25kWh for each bus. State of Charge profiles for each vehicle are shown in figure (36).

![Figure 36: Optimization Results for Scenario 2](image)
2.2.2 Cost Modeling

Capital costs charging complex/station has discussed in the Table 6.

a. Cost of Charging Infrastructure (Scenario I)

There will be two 75kW power chargers at two locations one at zone 5 (Zion Lodge) and the other at zone 9 (Temple of Sinawava). And one 50 kW charger at zone 10 (Bus Depot).

Table 6: Average Station Cost (75 kW) [72]

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>$3,000</td>
</tr>
<tr>
<td>Permit</td>
<td>$1,000</td>
</tr>
<tr>
<td>Utility Interconnection Cost</td>
<td>$10,000</td>
</tr>
<tr>
<td>Load Center and Meter Station</td>
<td>$2,000</td>
</tr>
<tr>
<td>DCFC Unit Hardware</td>
<td>$37,500</td>
</tr>
<tr>
<td>Conduit and Cables</td>
<td>$3,000</td>
</tr>
<tr>
<td>Concrete Pads, Materials &amp; Labor</td>
<td>$5,000</td>
</tr>
<tr>
<td>Accessory Material</td>
<td>$4,000</td>
</tr>
<tr>
<td>Site Surface &amp; Underground Work</td>
<td>$13,000</td>
</tr>
<tr>
<td>Fixed Site Improvements</td>
<td>$13,000</td>
</tr>
<tr>
<td>Equipment Installation Cost</td>
<td>$12,000</td>
</tr>
<tr>
<td>Project Management</td>
<td>$10,000</td>
</tr>
<tr>
<td>Total</td>
<td>$113,500</td>
</tr>
<tr>
<td>Number of Stations</td>
<td>2</td>
</tr>
<tr>
<td>Total for Two Stations</td>
<td>$227,000</td>
</tr>
</tbody>
</table>

Table 7: Average Station Cost (50 kW) [72]

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>$3,000</td>
</tr>
<tr>
<td>Permit</td>
<td>$1,000</td>
</tr>
<tr>
<td>Utility Interconnection Cost</td>
<td>$10,000</td>
</tr>
<tr>
<td>Load Center and Meter Station</td>
<td>$2,000</td>
</tr>
<tr>
<td>DCFC Unit Hardware</td>
<td>$25,000</td>
</tr>
<tr>
<td>Conduit and Cables</td>
<td>$3,000</td>
</tr>
<tr>
<td>Concrete Pads, Materials &amp; Labor</td>
<td>$5,000</td>
</tr>
<tr>
<td>Accessory Material</td>
<td>$4,000</td>
</tr>
<tr>
<td>Site Surface &amp; Underground Work</td>
<td>$13,000</td>
</tr>
<tr>
<td>Fixed Site Improvements</td>
<td>$13,000</td>
</tr>
<tr>
<td>Equipment Installation Cost</td>
<td>$12,000</td>
</tr>
<tr>
<td>Project Management</td>
<td>$10,000</td>
</tr>
<tr>
<td>Total</td>
<td>$101,000</td>
</tr>
<tr>
<td>Number of Stations</td>
<td>1</td>
</tr>
</tbody>
</table>

Scenario 1: Total Charging Infrastructure Cost = $227,000 + $101,000 = $328,000
b. Cost of Charging Infrastructure (Scenario II)

There will be two 75kW power chargers at zone 4 (Court of Patriarchs) and two more 25kW chargers of 25 at zone 9 (Temple of Sinawava)

Table 8: Average Station Cost (25 kW) [72]

| Engineering                  | $3,000 |
| Permit                       | $1,000 |
| Utility Interconnection Cost  | $10,000|
| Load Center and Meter Station| $2,000 |
| DCFC Unit Hardware           | $25,000|
| Conduit and Cables           | $3,000 |
| Concrete Pads, Materials & Labor| $5,000|
| Accessory Material           | $4,000 |
| Site Surface & Underground Work| $13,000|
| Fixed Site Improvements      | $13,000|
| Equipment Installation Cost  | $12,000|
| Project Management           | $10,000|
| Total                        | $101,000|
| Number of Stations           | 1 |

Table 9: Average Station Cost (75 kW) [72]

| Engineering                  | $3,000 |
| Permit                       | $1,000 |
| Utility Interconnection Cost  | $10,000|
| Load Center and Meter Station| $2,000 |
| DCFC Unit Hardware           | $75,000|
| Conduit and Cables           | $3,000 |
| Concrete Pads, Materials & Labor| $5,000|
| Accessory Material           | $4,000 |
| Site Surface & Underground Work| $13,000|
| Fixed Site Improvements      | $13,000|
| Equipment Installation Cost  | $12,000|
| Project Management           | $10,000|
| Total                        | $151,000|
| Number of Stations           | 1 |

**Scenario 2: Total Charging Infrastructure Cost = $101,000 + $151,000 = $252,000**

In both scenarios the Engineering costs include civil, structural and electrical engineering and assume significant reuse of non-site-specific work from other sites. Accessory materials include lighting, landscape plants and irrigation materials, signage and bollards. Site surface and underground work costs include grading, trenching/boring, pavement cutting, backfill and surface patching. Equipment installation cost include DCFC and ancillary electrical equipment installation [72].
c. Operational & Maintenance Cost

Operational and maintenance cost is calculated for propane fuel and electricity and the difference between these costs is used to calculate the total profit per year. And then this profit is used to calculate the payback period to replace the current propane buses by their electrical equivalents. The prices for propane and electricity are the current average prices of the fuel in United States of America.

Table 10: Operational and Maintenance Cost of Propane Fuel

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propane Fuel Cost ($/Gallon)</td>
<td>$2.4</td>
</tr>
<tr>
<td>Miles Per Year (miles/day * no of days)</td>
<td>28000</td>
</tr>
<tr>
<td>Propane Engine Efficiency (mpgge)</td>
<td>7</td>
</tr>
<tr>
<td>Energy Used Per Year (DGallon)</td>
<td>4000</td>
</tr>
<tr>
<td>Operation Cost $</td>
<td>$9600</td>
</tr>
<tr>
<td>Maintenance Cost ($/mile)</td>
<td>$1</td>
</tr>
<tr>
<td>Total Maintenance Cost $</td>
<td>$28000</td>
</tr>
<tr>
<td>Total Cost Par Year $</td>
<td>$37600</td>
</tr>
</tbody>
</table>

Table 11: Operational and Maintenance Cost of Electricity

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity Cost ($/kWh)</td>
<td>$0.12</td>
</tr>
<tr>
<td>Miles Per Year (miles/day * no of days)</td>
<td>28000</td>
</tr>
<tr>
<td>Battery Efficiency (kWh/mile)</td>
<td>0.747</td>
</tr>
<tr>
<td>Energy Used Per Year (kWh)</td>
<td>20916</td>
</tr>
<tr>
<td>Operation Cost $</td>
<td>$2509.92</td>
</tr>
<tr>
<td>Maintenance Cost ($/mile)</td>
<td>$0.2</td>
</tr>
<tr>
<td>Total Maintenance Cost $</td>
<td>$5600</td>
</tr>
<tr>
<td>Total Cost Par Year $</td>
<td>$8109.92</td>
</tr>
</tbody>
</table>

d. Purchase Cost

Table 12: Vehicle Purchase Including Battery Cost

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Vehicle Purchase Cost (Scenario I)</td>
<td>$1,757,000</td>
</tr>
<tr>
<td>Total Vehicle Purchase Cost (Scenario II)</td>
<td>$4,139,500</td>
</tr>
</tbody>
</table>
e. **Battery Cost**

Table 13: Battery Cost for Different Battery Size [4]

<table>
<thead>
<tr>
<th>Cost of Battery ($/kWh)</th>
<th>$ 300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Size 1 (kWh)</td>
<td>25</td>
</tr>
<tr>
<td>Battery Size 2 (kWh)</td>
<td>100</td>
</tr>
<tr>
<td>Battery Size 3 (kWh)</td>
<td>125</td>
</tr>
<tr>
<td>Total cost of Battery 1 ($)</td>
<td>$ 7500</td>
</tr>
<tr>
<td>Total cost of Battery 2 ($)</td>
<td>$ 30000</td>
</tr>
<tr>
<td>Total Cost of Battery 3 ($)</td>
<td>$ 37500</td>
</tr>
<tr>
<td>Total number of buses (Scenario I)</td>
<td>7</td>
</tr>
<tr>
<td>Total number of buses (Scenario II)</td>
<td>17</td>
</tr>
</tbody>
</table>

f. **Profit & Payback Period**

Table 14: Profit for All Scenario

<table>
<thead>
<tr>
<th>Profit</th>
<th>$29,490</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total All Buses Cost Savings (Scenario I)</td>
<td>$206,431</td>
</tr>
<tr>
<td>Total All Buses Cost Savings (Scenario II)</td>
<td>$501,331</td>
</tr>
</tbody>
</table>

Finally, the Payback Period is calculated with the following Formula 11:

\[
\text{Payback Period} = \frac{\text{Total Vehicle Purchase Cost} + \text{Total Charging Infrastructure Cost}}{\text{Total Profit}}
\]

(12)

Table 15: Payback Period

<table>
<thead>
<tr>
<th>Payback Period in Years (Scenario I)</th>
<th>10.10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payback Period in Years (Scenario II)</td>
<td>8.75</td>
</tr>
</tbody>
</table>

The payback period was calculated it includes the charging station infrastructure cost as well as the cost associated with the purchase of electric buses. It is the time required to recover total amount invested in vehicles as well as charging infrastructure. In scenario I 7 vehicles are replaced by electric buses and the payback period for the whole system is 10.10 years, and in scenario II all 17 vehicles are replaced by electric buses the payback period is 8.75 years.
2.2.3 Emissions Results for Bus (GREET)

Emissions results for light duty electric vehicle are plotted and compared with the conventional internal combustion engine vehicle. As we can see the VOC emissions are 0.14 g/mi and for diesel and propane vehicle it is 0.29 g/mi and 0.39 g/mi respectively which is much more than the electric vehicles. Also, CO2 WTW emissions showed 1.25 kg/mi for electric vehicle and it was 2.92 kg/mi and 1.54 kg/mi for diesel and propane vehicles. Same results are observed for Green House Gas emissions for electric vehicle the WTW GHG-100 emissions were 1.32 kg/mi and for diesel and propane are 3.04 kg/mi and 1.65 kg/mi. It clearly suggests that the WTW CO2 and GHG-100 emission for electric vehicle using Dynamic Wireless Power Transfer are much lesser than the conventional vehicle WTW CO2 and GHG-100 emissions. So, we can say that the electric vehicles are environmentally friendly as well as use of these vehicles will reduce the CO2 and Green House Gas emissions.

The results show that the emissions by Electric buses are much lesser than the Diesel-powered buses and currently operating Propane buses in Zion National Park.

<table>
<thead>
<tr>
<th>Emissions I</th>
<th>Electricity (g/mi)</th>
<th>Diesel (g/mi)</th>
<th>Propane (g/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOC</td>
<td>0.14</td>
<td>0.29</td>
<td>0.39</td>
</tr>
<tr>
<td>CO</td>
<td>0.44</td>
<td>0.92</td>
<td>9.39</td>
</tr>
<tr>
<td>NOx</td>
<td>0.87</td>
<td>2.01</td>
<td>1.25</td>
</tr>
<tr>
<td>CH4</td>
<td>2.45</td>
<td>3.58</td>
<td>3.1</td>
</tr>
</tbody>
</table>

Figure 37: Emissions I
Table 17: Emissions II

<table>
<thead>
<tr>
<th>Emissions II</th>
<th>Electricity (mg/mi)</th>
<th>Diesel (mg/mi)</th>
<th>Propane (mg/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2O</td>
<td>19.38</td>
<td>9.64</td>
<td>9.09</td>
</tr>
<tr>
<td>BC</td>
<td>5.54</td>
<td>10.14</td>
<td>7.84</td>
</tr>
<tr>
<td>POC</td>
<td>13.09</td>
<td>17.38</td>
<td>22.14</td>
</tr>
</tbody>
</table>

Figure 38: Emissions II

Table 18: Emissions III

<table>
<thead>
<tr>
<th>Emissions III</th>
<th>Electricity (kg/mi)</th>
<th>Diesel (kg/mi)</th>
<th>Propane (kg/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>1.25</td>
<td>2.92</td>
<td>1.54</td>
</tr>
<tr>
<td>GHG-100</td>
<td>1.32</td>
<td>3.04</td>
<td>1.65</td>
</tr>
</tbody>
</table>

Figure 39: Emissions III
Table 19: Emissions IV

<table>
<thead>
<tr>
<th>Emissions IV</th>
<th>Electricity (kg/mi)</th>
<th>Diesel (kg/mi)</th>
<th>Propane (kg/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PM10</td>
<td>0.16</td>
<td>79.67</td>
<td>54.49</td>
</tr>
<tr>
<td>PM2.5</td>
<td>67.51</td>
<td>68.75</td>
<td>47.6</td>
</tr>
</tbody>
</table>

Figure 40: Emissions IV

Table 20: Total Energy Used (WTW)

<table>
<thead>
<tr>
<th>Energy Used</th>
<th>Electricity (kJ/mi)</th>
<th>Diesel (MJ/mi)</th>
<th>Propane (kJ/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Energy</td>
<td>20</td>
<td>40</td>
<td>24</td>
</tr>
</tbody>
</table>

Figure 41: Total Energy Used (WTW)
3. TECHNICAL AND SUSTAINABILITY ANALYSIS OF IN-MOTION WIRELESS POWER TRANSFER

As transit buses travel fixed route and stops on the bus stops so that we can use that time to charge them at the stops but for to retrofit the roads to charge the buses while running on their route is not cost effective. But light duty electric vehicles can travel continuously without any stop and the to avoid the time required for charging the Dynamic Wireless Power Transfer (DWPT) comes into the picture. And if we will be using dynamic wireless power transfer to for LDEV then the same infrastructure buses can also use if they are driving the same route. To save the time for charging and travel longer distance with smaller batteries DWPT is good option for electrification.

3.1 Methodology

3.1.1 Methods

The project will start by developing validated vehicle models and incrementally expanding the system scope to include a large drive cycle database, inductive vs. capacitive In-Motion WPT models, an emission from geographic energy sources model, and lastly an economic cost and savings model of the In-Motion WPT infrastructure. This overall process is shown in Figure 42.

![Project Tasks](image)

Figure 42: Overall Project Procedures That Will Answer Research Questions

The overall project procedures shown in Figure 42 require completion of the following specific tasks:

Task 1. Create high-fidelity vehicle models using Python, MATLAB/Simulink software.

Task 2. Use Argonne National Laboratory’s (ANL) Autonomie vehicle modeling software to assist in model development by double-checking parameters, borrowing efficiency maps, etc. Note that Autonomie models do not provide flexibility to add other modeling aspects, thus the need to create new models in Simulink (Task 1).

Task 3. Compile a large drive cycle database of vehicle driving across many geographic regions using the National Renewable Energy Laboratory’s (NREL) general drive cycle database and Fleet DNA semi-truck drive cycle database. This also requires testing the Simulink developed models with various drive cycles to check for model fidelity.

Task 4. Develop, and incorporate in Simulink, a high-fidelity model of inductive In-Motion WPT based on systems proposed in high profile research papers in the field as well as systems used by desired future collaborators at USU and CU.
Task 5. Evaluate and incorporate ANL’s Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model which allows simulation of energy use and emissions output of conventional and electric vehicles.

Task 6. Develop an economic model of In-Motion WPT infrastructure installation costs, vehicle compatibility installation costs, fuel savings, environmental mitigation savings, and others to investigate the benefits of In-Motion WPT.

Note that current studies which include this large of a scope have very simple vehicle models and this project begins establishing a unique contribution to the In-Motion WPT field in Task 1.

3.1.2 In-Use Data

To obtain signals for drive input, a driving vehicle equipped with different sensors such as GPS, CAN data logger, and radar is driven on the route in Fort Collins, Colorado. In total, this route is 4 miles and should take 10-12 minutes per cycle, depending on traffic. The Fort Collins dataset was collected in October 2019 and contained data from repeated drives along a fixed route by the same driver [103].

![Drive Cycle Map of The Fort Collins Dataset](image)

This route represents the round trip on the following:

1. Parking Lot
2. West on Mulberry until Shields
3. South on Shields until Prospect
4. East on Prospect until College
5. North on College until Mulberry
6. West on Mulberry until Parking Lot
7. Parking Lot

The test generated Autonomous Driver Assistance System (ADAS) data for the vehicle forward cone from smart radar, which is a standard setup for production vehicle ADAS systems.
Test also generated the Vehicle to Infrastructure (V2I) data in the form of traffic signal information and segment travel times. The ego vehicle was specially instrumented research vehicle with the afore-mentioned ADAS sensors and a stereo camera with a Freematics logger. It is important to note that the timestep used for the analysis is 0.1 seconds.

3.1.3 Concept of In-Motion WPT

a. Infrastructure of In-Motion Wireless Power Transfer:

Covic and Boys (2013) defines the components of wireless charging EVs as:
1. The power-supply: which connects the system to the electric grid to receive power
2. The charging infrastructure or facility called a power track: which is an elongated track driven by the power supply’s current. Results in a magnetic field that follows the track
3. The pickup: which intercepts some of the magnetic field and converts it into controlled electricity
4. The load: which is the entity being charged by the electrical power [32,35]

b. General Working Principle:

➢ Power Transfer Side: Power Transfer side is the charging unit that transmits the power by electromagnetic field from the grid. It consists of:
   i) Transmitter Unit: Transmit power, under the road through WPT Pads
   ii) Power Supply Unit: Supply the power from the grid to the road surface. It consists of the power supply, the rectifier, the inverter and controller, power convertor etc

➢ Vehicle Side: Vehicle side receives the power from the power transmitter unit, consists of:
   i) Pickup Unit: To receive power it is attached at the bottom surface of the vehicle
   ii) Auxiliary Units: It consists of rectifiers and regulators, used to transmit the power from the pickup to the motor and battery.

![Figure 44: Working Concept of In-Motion Wireless Power Transfer](image-url)
3.1.4 High-Fidelity Model in Python

A high-fidelity backward-looking electric drivetrain model for Light Duty Electric Vehicle is developed in python. The model proceeds backward through the driveline, using the radius of the wheel to convert force and vehicle speed to torque and rotational speed. Torque and speed are divided and multiplied by gear ratios of the differential and transmission before an engine torque and speed are used to obtain the motor efficiency from a map. Further details of the model are given in [104,105]. Model parameters are listed in the Table 3. We tried different combinations of mass, drag coefficient, and rolling resistance coefficient to calibrate the electric drivetrain model and get the best possible result out of the different combinations we tried which are shown in detail in next section.

Two different Battery Size LDEV models i) Toyota Prius Prime ii) Toyota Prius Plug-In Hybrid were tested for Dynamic Wireless Power Transfer on route in Fort Collins, Colorado.

To create the model of electric vehicle, the publicly available parameters of Toyota Prius shown in table were used in the High-Fidelity Model in Python for vehicle modeling. Parameters for the vehicle are given below:

Table 21: Mechanical Parameters for Vehicle Modeling

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Mass</td>
<td>1580.87 kg</td>
</tr>
<tr>
<td>Maximum Engine Power</td>
<td>73 kW</td>
</tr>
<tr>
<td>Max Traction EM Speed</td>
<td>13,500 rpm</td>
</tr>
<tr>
<td>Coefficient of Drag</td>
<td>0.259</td>
</tr>
<tr>
<td>Frontal Area</td>
<td>2.6005 m^2</td>
</tr>
<tr>
<td>Coefficient of Rolling Resistance</td>
<td>0.008</td>
</tr>
<tr>
<td>Final Drive Ratio</td>
<td>3.543</td>
</tr>
<tr>
<td>Ring Gear Number of Teeth</td>
<td>78</td>
</tr>
<tr>
<td>Sun Gear Number of Teeth</td>
<td>30</td>
</tr>
<tr>
<td>Wheel Radius</td>
<td>0.317 m</td>
</tr>
</tbody>
</table>

Battery parameters for both Toyota Prius Prime and Toyota Plug-In Hybrid are mentioned in the table 22 below.

Table 22: Battery Parameters

<table>
<thead>
<tr>
<th>Vehicle Model</th>
<th>Battery Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyota Prius Prime</td>
<td>8.8 kWh</td>
</tr>
<tr>
<td>Toyota Prius Plug-In Hybrid</td>
<td>4.4 kWh</td>
</tr>
</tbody>
</table>

The following figure shows the Logged Speed vs Time and figure shows the Distance vs Time for one drive instance.
3.1.5 Model Calibration

A backward-looking drivetrain model has been created, tuned and validated model with the data from route in Fort Collins, Colorado.
In the above figure we can see that the modeled speed is exactly matching with the logged speed from the drive data. So, we can say that the model is validated and can use for further simulations such as to calculate the energy consumption for that particular drive cycle, SOC and other parameters.

Figure 48 shows the total energy consumption for the one drive using an electric vehicle model with a battery size of 50 kWh.
3.1.6 Energy Consumption Calculation

With the calibrated electric drivetrain model, we calculated the energy consumption for two different cases one using the Toyota Prius Prime model and the other for the Toyota Plug-In Hybrid. And calculated the energy consumption in kilowatt-hour per mile (kWh/mile).

a. Case I: Toyota Prius Prime

In first test case we used a Toyota Prius Prime with Battery Size 8.8 kWh. And the starting SOC was 23%. The energy required to complete the route of 4 mile was 1.024013 kWh without the auxiliary energy consumption. So, it uses 0.26 kWh/mile energy.

The energy consumption in kWh and the SOC in percentage is shown in the figures below.

![Figure 49: Energy Consumption for Toyota Prius Prime](image1)

![Figure 50: SOC Profile for Toyota Prius Prime](image2)
b. Case II: Toyota Prius Plug-In Hybrid

In second test case we used a Toyota Prius Prime with Battery Size 4.4 kWh. And the starting SOC was 35%. The energy required to complete the route of 4 mile was 1.024013 kWh without the auxiliary energy consumption. So, it uses 0.26 kWh/mile energy.

The energy consumption in kWh and the SOC in percentage is shown in the figures below.

Figure 51: Energy Consumption for Toyota Prius Plug-In Hybrid

Figure 52: SOC Profile for Toyota Prius Plug-In Hybrid
3.1.7 Wireless Power Transfer Configuration

As Inductive Wireless Power Transfer (IWPT) has several advantages over Capacitive Wireless Power Transfer. And IWPT is tested in real life for higher power transfer so it is used for the further simulation purpose.

The parameters like size, shape and gap between coils, resonating frequency, and the final load may have impact on the power transfer. Capacitors are applied both on primary and secondary side considering operating frequency is equal to the resonant frequency to maximize the power transfer and minimize the leakage inductance. Compensation of primary winding allows to reduce the switching losses and VA rating of supply and with that compensation of secondary winding allows to increase power transfer. By doing these things huge electromagnetic field can be generated at the transmitting coil as the current flowing through the transmitting coil reaches higher value. And the power is transferred to the load with high efficiency as the two coils will generate a very strong magnetic coupling resonance [107,108].

According to the different compensation topology of transmission coils there are four main configurations [107,108]:

1. Series-series (SS);
2. Series-parallel (SP);
3. Parallel-Series (PS);
4. Parallel-Parallel (PP).

A series-parallel configuration is used to develop an inductive wireless power transfer system.

IPT Configuration

Figure 53: IPT Configuration
To minimize switching losses and converter VA rating two compensating elements the LC configuration does not provide enough degrees of freedom. LCL- Compensation Double-Sided is used in above configuration to increase the efficiency of the system.

![Diagram of LCL Compensation](image)

Figure 54: Double-Sided LCL-Compensation

In primary and secondary side, a coil is added in series. To reduce the inverter current harmonics inductance has used. In this configuration system should work at unitary power factor. The filter inductances are used to resonate at the same resonant frequency of the wireless system to obtain constant primary current operation. This configuration achieves a constant current operation, high efficiency at light loads and harmonics filtering capabilities because it is composed of more passive components [108].

The primary and secondary LCL compensation parameters and transformer parameters are shown in the Table 23.

<table>
<thead>
<tr>
<th>Table 23: LCL Compensation Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>General Parameters</strong></td>
</tr>
<tr>
<td>DC Bus Voltage [V]</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
</tr>
<tr>
<td>IGBT Duty Cycle [%]</td>
</tr>
<tr>
<td>Series Inductance (LPs) [μH]</td>
</tr>
<tr>
<td>Series Resistance (RPs) [mΩ]</td>
</tr>
<tr>
<td>Primary Parallel Capacitance (CPp) [mF]</td>
</tr>
<tr>
<td>Secondary Parallel Capacitance (CSp) [mF]</td>
</tr>
<tr>
<td>Load Resistance (R) [Ω]</td>
</tr>
</tbody>
</table>

| **Transformer**                       |                                            |
| Primary Self-inductance [μH]          | 100                                         |
| Secondary Self-inductance [μH]        | 350                                         |
| Coupling Coefficient [-]              | 0.62                                        |

With these parameters calculated the results for Input Current, Input Voltage, Output Current, Output Voltage, Output Power, Mean Output Power, Efficiency of Power Transfer, etc. The results are plotted below in the results subsection.
3.1.8 Incorporating IPT to Electric Vehicle Model on the Route

As we got an IPT model ready with 50kW mean output power we can incorporate that IPT model to the electric drivetrain model to check how it works and to see the results for vehicle charging when it is driving the route in Fort Collin, Colorado.

To perform this action, we have two different vehicle models one is Toyota Prius Prime and the other is Toyota Prius Plug-In Hybrid. Also, we have considered different scenario as percentage of road electrification from 50% to 100% to check the status of system and the final State of Charge for each scenario after completing the one drive instance.

3.1.9 Incorporating Greet Model to Calculate the Emissions and Energy Use

ANL’s Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model is used to calculate the emissions for different fuel technologies and compare it with electric bus emissions results.

The outputs from GREET Model are GHG emissions (CO₂, CH₄, N₂O, and total CO₂e), Energy use (total, fossil petroleum, coal, natural and renewable energy), Emissions of criteria pollutants (VOC, CO, NOₓ, PM₁₀, PM₂.5 and SOₓ); separated into total and urban emissions. Emissions are calculated for 12,000 vehicle miles traveled for a year for each fuel type and then compared the results.

We have considered 12000 vehicle miles traveled by a light duty electric vehicle throughout the year and calculated Well-to-Wheel (WTW) the emissions and energy use. Also calculated the emissions and energy use for similar number of miles traveled for conventional gasoline and diesel light duty vehicle. Then compared the emission results from electric vehicles (WTW) with conventional vehicle emissions results and found that the CO₂ emission as well as GHG emissions were much lesser in electric vehicles.

3.1.10 Cost Estimation

Cost estimation for Light Duty Electric Vehicle (LDEV) and Light Duty ICE Vehicle (LDICE) has been done.

The cost model consists of the infrastructure cost and it also discuss about the purchase cost, operating cost and maintenance cost for the electric vehicle. And compared the operating cost and maintenance cost with the conventional gasoline vehicle to calculate the profit by replacing the conventional gasoline vehicle with the reduced battery sized electric vehicle.

The table below shows the components price for components and cost for electronics and we can calculate the retrofitting cost from it.
Table 24: Component Cost for Electronics and Retrofitting [109]

<table>
<thead>
<tr>
<th>Parameter/Component</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Road retrofitting cost (M$/lane.mile)</td>
<td>1</td>
</tr>
<tr>
<td>Electronics and material cost (M$/lane.mile.kW)</td>
<td>0.0273</td>
</tr>
<tr>
<td>Grid inverter cost (M$/lane.mile.kW)</td>
<td>0.015</td>
</tr>
<tr>
<td>Installation cost (M$/position)</td>
<td>0.005</td>
</tr>
<tr>
<td>Vehicle wireless components cost ($/kW)</td>
<td>29</td>
</tr>
<tr>
<td>Wireless charging rate (kW)</td>
<td>14.5</td>
</tr>
</tbody>
</table>

**DWPT Formulas:**

Total infrastructure cost = \((\text{Road retrofitting cost} \times \text{Number of lanes} \times \% \text{Electrification of Roadway Required}) + (\text{Electronics and material cost} \times \text{Number of lanes} \times \% \text{Electrification of Roadway Required} \times \text{Wireless charging rate}) + (\text{Grid inverter cost} \times \text{Number of lanes} \times \% \text{Electrification of Roadway Required} \times \text{Wireless charging rate}) + (\text{Installation cost} \times \text{Number of positions})\) [109]

Total Energy Required (kWh) = Total Distance Traveled (Total miles/year) \times kWh/mile for LDEV

Total Fuel Required (gallons) = Total Distance Traveled (Total miles/year) \times gallon/mile for LDICE

Total operating cost for LDEV = Total Energy Required \times Cost of Electricity

Total operating cost for LDICE = Total Fuel Required \times Cost of Fuel

Maintenance Cost for LDEV = 2% of purchase cost every year for LDEV

Maintenance Cost for LDICE = 4% of purchase cost every year for LDICE

Total cost per year LDEV = Total operating cost for LDEV + Maintenance Cost for LDEV

Total cost per year LDICE = Total operating cost for LDICE + Maintenance Cost for LDICE

Net Profit LD = Total cost per year LDICE - Total cost per year LDEV

Profit Share towards infrastructure = 0.75

Net Profit = (Net Profit LD) \times Profit Share towards infrastructure
3.2 Results

3.2.1 Results from IPT Configuration

The results from the IPT Configuration has shown in the figures from (55) to (59).

Figure 55: Input Voltage and Input Current

Figure 56: Output Voltage and Output Current
Figure 57: Output Power

Figure 58: Mean Output Power

Figure 59: Efficiency
As we can see in previous graphs, peak power output results to be about 62 kW during transient conditions and 60 kW in steady state. And mean power output is 50 kW at steady state. And the efficiency is 80%.

3.2.2 SOC Results

**Scenario 1: Prius Prime**

We first drove the route from Fort Collins, Colorado without any charging on route with Toyota Prius Prime with battery size of 8.8 kWh. Checked for different cases for in-motion wireless power transfer considering different percentage of road electrification. And compared the results with no in-motion wireless power transfer scenario.

- Charging Power = 50 kW
- Battery Size = 8.8 kWh
- Starting Initial SOC = 23%
- Road Length = 4 miles

The State of Charge (SOC) level was 23% at the start of the drive cycle and it ends the at 11.19% after driving the route. And after that ran the simulation for Dynamic Wireless Power Transfer with charging power of 50 kW. In that we have considered different scenarios of road electrification from 50% to 100%. As the route is smaller so considered the road coverage more than 50% to see the significant changes in the SOC for each scenario after the end of the drive cycle with In-Motion Wireless power Transfer. As the road coverage percentage increases the final SOC level after the end of the drive cycle increases. That means on 100% electrification of that 4-mile route gives the maximum State of Charge at the end of drive cycle. On 100% electrification after driving the wireless power transfer route the final SOC reads 45.74%. Whereas for 50% road coverage the SOC shows reading 20.88%. And the cases in between 50% and 100% the SOC increases as the road electrification percentage increases.

And in each scenario of In-Motion Wireless Power Transfer the SOC is greater than the SOC without any charging on the same route.

<table>
<thead>
<tr>
<th>Charging Power (kW)</th>
<th>Road Coverage (%)</th>
<th>Final SOC (%)</th>
<th>Increase in SOC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>11.196116</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>20.885748</td>
<td>9.689632</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
<td>25.856455</td>
<td>14.66034</td>
</tr>
<tr>
<td>50</td>
<td>70</td>
<td>30.827163</td>
<td>19.63105</td>
</tr>
<tr>
<td>50</td>
<td>80</td>
<td>35.797870</td>
<td>24.60175</td>
</tr>
<tr>
<td>50</td>
<td>90</td>
<td>40.768577</td>
<td>29.57246</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
<td>45.739284</td>
<td>34.54317</td>
</tr>
</tbody>
</table>
Figure 60: Speed Profile (Scenario I)

Figure 61: Final SOC Without DWPT (Scenario I)

Figure 62: Final SOC for Each Case (Scenario I)
Scenario 2: Prius Plug-In Hybrid

We first drove the route from Fort Collins, Colorado without any charging on route with Toyota Prius Plug-In Hybrid with battery size of 4.4 kWh. Similar to scenario 1 here also we checked for different cases for in-motion wireless power transfer considering different percentage of road electrification. And compared the results with no in-motion wireless power transfer scenario.

- Charging Power = 50 kW
- Battery Size = 4.4 kWh
- Starting Initial SOC= 35%
- Road Length = 4 miles

The State of Charge (SOC) level was 35% at the start of the drive cycle and it ends the at 11.39% after driving the route. And after that ran the simulation for Dynamic Wireless Power Transfer with charging power of 50 kW. In that we have considered different scenarios of road electrification from 50% to 100%. As the route is smaller so considered the road coverage more than 50% to see the significant changes in the SOC for each scenario after the end of the drive cycle with In-Motion Wireless power Transfer. As the road coverage percentage increases the final SOC level after the end of the drive cycle increases. That means on 100% electrification of that 4-mile route gives the maximum State of Charge at the end of drive cycle. On 100 % electrification after driving the wireless power transfer route the final SOC reads 98.41%. Whereas for 50% road coverage the SOC shows reading 25.92%. And the cases in between 50% and 100% the SOC increases as the road electrification percentage increases.

In this scenario also with Toyota Plug-In Hybrid in each case of In-Motion Wireless Power Transfer the SOC is greater than the SOC without any charging on the same route.

The Table (26) shown below explains the different cases of road coverage and the corresponding SOC results with the given charging power used for In-Motion Wireless Power Transfer.

<table>
<thead>
<tr>
<th>Charging Power (kW)</th>
<th>Road Coverage (%)</th>
<th>Final SOC (%)</th>
<th>Increase in SOC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>11.392231</td>
<td>-</td>
</tr>
<tr>
<td>50</td>
<td>50</td>
<td>25.916766</td>
<td>14.5245</td>
</tr>
<tr>
<td>50</td>
<td>60</td>
<td>40.414662</td>
<td>29.0224</td>
</tr>
<tr>
<td>50</td>
<td>70</td>
<td>54.912557</td>
<td>43.5203</td>
</tr>
<tr>
<td>50</td>
<td>80</td>
<td>69.410453</td>
<td>58.0182</td>
</tr>
<tr>
<td>50</td>
<td>90</td>
<td>83.908349</td>
<td>72.5161</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
<td>98.406244</td>
<td>87.014</td>
</tr>
</tbody>
</table>
Figure 63: Speed Profile (Scenario II)

Figure 64: Final SOC Without DWPT (Scenario II)

Figure 65: Final SOC for Each Case (Scenario II)
3.3.3 Emission Results

Emissions results for light duty electric vehicle are plotted and compared with the conventional internal combustion engine vehicle. As we can see the VOC emissions are 0.01561 g/mi and for diesel and gasoline vehicle it is 0.14 g/mi and 0.25 g/mi respectively which is way more than the electric vehicles. Same goes with other emissions as well. CO2 WTW emissions showed 0.14 kg/mi for electric vehicle and it was 0.33 kg/mi and 0.35 kg/mi for diesel and gasoline vehicles. Same results are observed for Green House Gas emissions for electric vehicle the WTW GHG-100 emissions were 0.15 kg/mi and for diesel and gasoline are 0.35 kg/mi and 0.36 kg/mi. It clearly suggests that the WTW CO2 and GHG-100 emission for electric vehicle using Dynamic Wireless Power Transfer are much lesser than the conventional vehicle WTW CO2 and GHG-100 emissions. So, we can say that the electric vehicles are environmentally friendly as well as use of these vehicles will reduce the CO2 and Green House Gas emissions.

The emissions results are grouped in tables and plotted in figures shown below.

Table 27: Emissions I

<table>
<thead>
<tr>
<th>Emissions I</th>
<th>Electricity (g/mi)</th>
<th>Diesel (g/mi)</th>
<th>Gasoline (g/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VOC</td>
<td>0.01561</td>
<td>0.14</td>
<td>0.25</td>
</tr>
<tr>
<td>CO</td>
<td>0.04946</td>
<td>2.85</td>
<td>2.77</td>
</tr>
<tr>
<td>NOx</td>
<td>0.09688</td>
<td>0.23</td>
<td>0.25</td>
</tr>
<tr>
<td>CH4</td>
<td>0.27</td>
<td>0.5</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Figure 66: Emissions I
Table 28: Emissions II

<table>
<thead>
<tr>
<th>Emissions II</th>
<th>Electricity (mg/mi)</th>
<th>Diesel (mg/mi)</th>
<th>Gasoline (mg/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N2O</td>
<td>2.16</td>
<td>1.47</td>
<td>17.03</td>
</tr>
<tr>
<td>BC</td>
<td>0.62</td>
<td>1.89</td>
<td>2.34</td>
</tr>
<tr>
<td>POC</td>
<td>1.46</td>
<td>2.27</td>
<td>4.53</td>
</tr>
</tbody>
</table>

Figure 67: Emissions II

Table 29: Emissions III

<table>
<thead>
<tr>
<th>Emissions III</th>
<th>Electricity (kg/mi)</th>
<th>Diesel (kg/mi)</th>
<th>Gasoline (kg/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO2</td>
<td>0.14</td>
<td>0.33</td>
<td>0.35</td>
</tr>
<tr>
<td>GHG-100</td>
<td>0.15</td>
<td>0.35</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Figure 68: Emissions III

60
Table 30: Total Energy Used (WTW)

<table>
<thead>
<tr>
<th>Energy Used</th>
<th>Electricity (kJ/mi)</th>
<th>Diesel (kJ/mi)</th>
<th>Gasoline (kJ/mi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Energy (WTW)</td>
<td>2246</td>
<td>4507</td>
<td>5025</td>
</tr>
</tbody>
</table>

Figure 69: Total Energy Used (WTW)

Table 31: Reduction (yearly)

<table>
<thead>
<tr>
<th>Reduction (Yearly)</th>
<th>CO2 (kg/year)</th>
<th>GHG-100 (kg/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel-Electric Comparison</td>
<td>2280</td>
<td>2400</td>
</tr>
<tr>
<td>Gasoline-Electric Comparison</td>
<td>2520</td>
<td>2520</td>
</tr>
</tbody>
</table>

Figure 70: Reduction (Yearly)
3.3.4 Cost Estimation Results

We have calculated the operating and maintenance cost for electric vehicle with lesser batteries and compared with the conventional vehicle. We found that the operational and maintenance cost for electric vehicles is much lesser than the conventional vehicles. For this also we have used the cost for two battery sized vehicles those are Toyota Prius Prime and Toyota Prius Plug-In Hybrid. The cost saving is calculated after giving certain amount of money towards infrastructure cost to recover that money as well. 25 percent of the profit share is contributed towards the infrastructure cost. As the route used to drive the vehicle and test all the scenarios was smaller, we did not calculate the payback period. We just calculated the road retrofitting cost required to calculate the payback period if we can implement it on a bigger route.

Table 32: Operating and Maintenance Cost for Toyota Prius Prime

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Electric Vehicle</th>
<th>ICE Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Cost ($)</td>
<td>374.4</td>
<td>990</td>
</tr>
<tr>
<td>Maintenance Cost ($)</td>
<td>548.72</td>
<td>1400</td>
</tr>
</tbody>
</table>

Table 33: Profit and Share Towards Infrastructure for Toyota Prius Prime

| Cost Saverings ($) | 1466.89 |
| Share Towards Infrastructure ($) | 366.72 |
| Net Profit ($) | 1100.17 |

Table 34: Operating and Maintenance Cost for Toyota Prius Plug-In Hybrid

<table>
<thead>
<tr>
<th>Cost ($)</th>
<th>Electric Vehicle</th>
<th>ICE Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Cost ($)</td>
<td>374.4</td>
<td>990</td>
</tr>
<tr>
<td>Maintenance Cost ($)</td>
<td>543.57</td>
<td>1400</td>
</tr>
</tbody>
</table>

Table 35: Profit and Share Towards Infrastructure for Toyota Prius Plug-In Hybrid

| Cost Savings ($) | 1472.03 |
| Share Towards Infrastructure ($) | 368 |
| Net Cost Savings ($) | 1104.03 |
4. SUMMARY

An operationally feasible system to replace conventional buses with their battery-electric equivalents is designed by simulating electric bus operation, identifying charging opportunities, and optimizing the charging operations to minimize operating costs. A calibrated Battery Electric Bus (BEB) model, geo-fencing, and Mixed Integer Linear Programming (MILP) were used, respectively, for each facet of the study. The result is a controlled charging schedule for each bus operating in the fleet. In this research work, for planning an on-route fast-charging system an advanced optimization model has brought into the picture, to find an optimal number of chargers for the fleet depot and stops on-route, and to find an optimal set of vehicle battery sizes to minimize capital costs while replacing multiple vehicles with their electrical equivalents, a technique known as Mixed-Integer Linear Programming is used to find an optimal charging strategy. In electrification of mass transit buses this study helps to understand the technical feasibility of the on-route fast charging of battery electric buses.

Also, the detailed economic analysis has been done to calculate the payback period for whole system i.e. buses and charging infrastructure. ANL’s Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) Model was also used to calculate the emissions for different fuel technologies. The results were compared it with electric bus emissions results, and which colludes that the emissions and environmental pollution is much lesser due Electric buses (WTW) than the conventional diesel buses and currently operating propane buses in Zion National Park.

In study II high fidelity model of electric vehicle model has been developed in python and Simulink model for Inductive Wireless Power transfer (IPT) has been studied, different combinations are developed and one out of those configurations were used to run further simulations. Calculated the energy use with the electric vehicle model. Then incorporated the IPT model to charge electric vehicle on-route while driving. Simulated different percentage of road coverage with two Toyota Prius model. Calculated the cost for road infrastructure, retrofitting, operational and maintenance cost for DWPT system and compared with the conventional vehicle technology to explain the benefits. GREET model studied and used to calculate emissions, energy used for different vehicle type, different fuel type and compared all results and results shows that electric vehicles emissions are much lesser than the conventional vehicles.
5. CONCLUSION AND FUTURE WORK

Study combines the Bus electrification and DWPT study by incorporating it with the vehicle model and doing the economic and environmental analysis of the system to study its impact commercially as well as environmentally. Reduced the energy consumption by reducing onsite weight of battery using fast charger on-route. Also results in reduced operating cost, maintenance cost and emissions using fast charger on-route for transit bus. In electrification of mass transit buses this study helps to understand the technical feasibility of the on-route fast charging of battery electric buses. Study II which is Dynamic Wireless Power Transfer (DWPT) is solution for the range anxiety in Light Duty Electric Vehicles. Also, DWPT helps to reduce the battery size and the weight thereby reduces energy consumption. Electric vehicles using DWPT reduces the emissions, operational and maintenance cost compared to ICEV. Capacitive WPT is also a great alternative as it is less expensive, and the expected results suggest. Inductive WPT have great potential to improve transportation sustainability. Bus electrification and In-Motion Wireless Power transfer is very economic, eco-friendly & efficient technique for transportation. It is expected that outcomes of the study will show that electrification and in-motion charging using WPT presents both economic and environmental advantages when contrasted with ordinary ICE transportation and a long range EV fleet. The cost of fuels like petrol, diesel etc. has been steadily increasing due to increased number of vehicles and proportional excess usage of fuel and limited sources of fossil fuel. Depleting sources of these fuels are also a major concern. The age-old designs of vehicles are the major contributors to the problem of greenhouse gases. The future of automotive technologies is moving toward electric vehicles which are considered as a replacement to oil-powered internal combustion engine driven vehicles, keeping in mind CO2 reduction.

In overall conclusion we can say that with Bus Electrification and DWPT we can replace fossil fuels by electricity as the standard fuel for vehicles at major extent. From literature study and based on research results from study I and study II we can say that Transit Bus Electrification & In-Motion WPT is very economic, eco-friendly & efficient technique for transportation.

Future Work

Future work for the bus electrification study is to optimize the results for the bus stops where the bus stops the most throughout the day’s operation instead of considering all the bus stops as charging opportunity. And compare the results with the current scenario and the effects on cost. Also, Study additional datasets are available for shuttles operating within the national parks system.

The future work for the dynamic wireless power transfer study includes addition of auxiliary energy consumption to traction energy consumption. As the drive cycle used in this study is a little short so use a longer drive cycle data and use different drive cycles to see the effects/changes in the results. Also, this study talks about a single type of vehicle we can incorporate this to different vehicle models as well as to different vehicle types including the heavy-duty vehicles. A 50-kW charging power is used in Dynamic Wireless power Transfer study we can check for different power levels and its effects on the battery size and road electrification percentage.
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63. Li, Siqi, and Chunting Chris Mi. "Wireless power transfer for electric vehicle applications." IEEE journal of emerging and selected topics in power electronics 3, no. 1 (2014): 4-17.
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110. Fuel consumption data from U.S. Department of Energy as of Oct 2018
APPENDIX

A.  Toyota Prius Prime

%%%DWPT clear all; close all; clc
DeltaSOC=20;
RM = 1; % road length (mile)
ER = (100 * RM)/100; % Electrification_Required
N_evs=20600; % number of the EVs utilizing the WPT system per 300 miles
N_pads=1; % number of vehicle pads
N_lanes=2; % number of electrified lanes %(one on each side)%

%%% DWPT Design
Q_b_LDEV = 8.8; % battery capacity (kWh)
P_c= 50; % wireless charging rate (kW)
E_c= 0.26; % Energy consumption (kWh/mile without auxiliary use)
N_positions=((1/RM)*RM); % # DWPT positions/300 mile
delta=1; % road
B_CPkWh = 300; % Battery cost per kWh

C_rate_LDEV=0.9*P_c/Q_b_LDEV; % charging rate for (10-90% SOC)

% road infrastructure cost
c_r=1; % road retrofitting cost (M$/lane.mile)
c_e=0.0273; % electronics and material cost (M$/lane.mile.kW)
c_g=0.015; % grid inverter cost (M$/lane.mile.kW)
c_iD=0.005; % installation cost (M$/position)
c_VA=29; % vehicle wireless components cost ($/kW)

if DeltaSOC == 20
% c_b= 1.2*84.05*exp(0.0644*C_ratem); % fitted cost coefficient ($/kWh) with Delta SOC=20% considering current price 103 $/kW
  c_b_LDEV= 1.2*63.152*exp(0.0764*C_rate_LDEV); % fitted cost coefficient %($/kWh) with Delta SOC=20% considering DOE target 80 $/kW
end

Bat_Cost_LDEV = Q_b_LDEV*c_b_LDEV;

TCR_F = (c_r*N_lanes*ER) + (c_e*N_lanes*ER*P_c) + (c_g*N_lanes*ER*P_c) ... + (c_iD*N_positions);
% LDEV_kWh_per_mile #(kWh/mile)
Eng_LDEV = 0.26;
% Average_Distance_Traveled_P = 12000 % (Private_Vehicles)
Dist_T_LDEV = 12000;
% Total Energy Required (kWh) = Total Distance Traveled * kWh/mile for LDEV
Eng_T_LDEV = Dist_T_LDEV * Eng_LDEV;
% Cost of Electricity ($/kWH)
Cost_Electricity = 0.12;
% Total operating cost ($/year)
Opr_T_Cost_LDEV = Eng_T_LDEV * Cost_Electricity;
Cost_1_LDEV = (25000 + (Bat_Cost_LDEV) + (c_VA*P_c));% Price of 1 light duty electric vehicle
% Total purchase cost ($) 
Pur_T_Cost_LDEV = Cost_1_LDEV * 1;
% Battery change cost (once in every 10 years)
Bat_Cost_LDEV = Q_b_LDEV*c_b_LDEV*1;
% Maintenance Cost (2% of puchase cost every year)
Man_T_Cost_LDEV = (Pur_T_Cost_LDEV * 2/100);
% Total cost per year
TCPY_LDEV = Opr_T_Cost_LDEV + Man_T_Cost_LDEV;
% Total cost for 10 years
TC10Y_LDEV = 10*Opr_T_Cost_LDEV + 10*Man_T_Cost_LDEV;

% ICEV_gallon_per_mile #(gallon/mile)
Eng_LDICE = 0.033; % (30 miles/gallon)
% Average_Distance_Traveled_P = 12000 % (Private_Vehicles)
Dist_T_LDICE = 12000;
% Total Fuel Required (gallons) = Total Distance Traveled * gallon/mile for LDICE
Eng_T_LDICE = Dist_T_LDICE * Eng_LDICE;
% Cost of Fuel ($/gallon)
Cost_Fuel = 2.5;
% Total operating cost ($/year)
Opr_T_Cost_LDICE = Eng_T_LDICE * Cost_Fuel;
Cost_1_LDICE = 35000; % Price of 1 Light Duty ICE Vehicle
% Total purchase cost ($) 
Pur_T_Cost_LDICE = Cost_1_LDICE * 1;
% Battery change cost (once in every 10 years = 40% of purchase cost)
% Maintenance Cost (4% of puchase cost every year)
Man_T_Cost_LDICE = (Pur_T_Cost_LDICE * 4/100);
% Total cost per year
TCPY_LDICE = Opr_T_Cost_LDICE + Man_T_Cost_LDICE;
% Total cost for 10 years
TC10Y_LDICE = 10*Opr_T_Cost_LDICE + 10*Man_T_Cost_LDICE;

Diff_Pur_Cost_LD = Pur_T_Cost_LDICE - Pur_T_Cost_LDEV;
Profit_Share = 0.75;

Net_Profit_LD = TCPY_LDICE - TCPY_LDEV;

Net_Profit = (Net_Profit_LD)*Profit_Share;

Results

% Generated by MATLAB on 30-Apr-2020 23:54:10
% MATLAB version: 9.6.0.1114505 (R2019a) Update 2
% -------------------------------------------------------------------

B_CPKWh = 300;

Bat_Cost_LDEV = 985.64831786003663;

C_rate_LDEV = 5.1136363636363633;

Cost_1_LDEV = 27435.648317860036;

Cost_1_LDICE = 35000;

Cost_Electricity = 0.12;

Cost_Fuel = 2.5;

DeltaSOC = 20;

Diff_Pur_Cost_LD = 7564.3516821399644;

Dist_T_LDEV = 12000;

Dist_T_LDICE = 12000;

ER = 1;

E_c = 0.26;

Eng_LDEV = 0.26;

Eng_LDICE = 0.033;
Eng_T_LDEV = 3120;
Eng_T_LDICE = 396;
Man_T_Cost_LDEV = 548.71296635720068;
Man_T_Cost_LDICE = 1400;
N_evs = 20600;
N_lanes = 2;
N_pads = 1;
N_positions = 1;
Net_Profit = 1100.1652752320997;
Net_Profit_LD = 1466.8870336427995;
Opr_T_Cost_LDEV = 374.4;
Opr_T_Cost_LDICE = 990;
P_c = 50;
Profit_Share = 0.75;
Pur_T_Cost_LDEV = 27435.648317860036;
Pur_T_Cost_LDICE = 35000;
Q_b_LDEV = 8.8;
RM = 1;
TC10Y_LDEV = 9231.1296635720064;
TC10Y_LDICE = 23900;
TCPY_LDEV = 923.11296635720066;
TCPY_LDICE = 2390;
TCR_F = 6.235;
c_VA = 29;
c_b_LDEV = 112.00549066591324;
c_e = 0.0273;
c_g = 0.015;
c_iD = 0.005;
c_r = 1;
delta = 1;
B. Toyota Prius Plug-In Hybrid

clear all;
close all;
cic
DeltaSOC=20;
RM = 1; % road length (mile)
ER = (100 * RM)/100; % Electrification_Required
N_evs=20600; % number of the EVs utilizing the WPT system per 300 miles
N_pads=1; % number of vehcile pads
N_lanes=2; % number of electrified lanes %(one on each side)%

% DWPT Design
Q_b_LDEV = 4.4; % battery capacity (kWh)
P_c= 50; % wireless charging rate (kW)
E_c= 0.26; % Energy consumption (kWh/mile without auxiliary use)
N_positions=((1/RM)*RM); % # DWPT positions/300 mile
delta=1; % road
B_CPkWh = 300; % Battery cot per kWh

C_rate_LDEV=0.9*P_c/Q_b_LDEV; % charging rate for (10-90% SOC)

% road infrastrcuture cost
C_r=1; % road retrofitting cost (M$/lane.mile)
C_e=0.0273; % electronics and material cost (M$/lane.mile.kW)
C_g=0.015; % grid inverter cost (M$/lane.mile.kW)
C_iD=0.005; % installation cost (M$/position)
C_VA=29; % vehicle wireless components cost ($/kW)

if DeltaSOC == 20
    c_b= 1.2*84.05*exp(0.0644*C_rate_LDEV); % fitted cost coefficient ($/kWh) with Delta SOC=20% considering current price 103 $/kW
    c_b_LDEV= 1.2*63.152*exp(0.0764*C_rate_LDEV); % fitted cost coefficient %($/kWh) with Delta SOC=20% considering DOE target 80 $/kW
end

Bat_Cost_LDEV = Q_b_LDEV*c_b_LDEV;

TCR_F = (C_r*N_lanes*ER) + (C_e*N_lanes*ER*P_c) + (C_g*N_lanes*ER*P_c) ... + (C_iD*N_positions);

% LDEV_kWh_per_mile #(kWh/mile)
Eng_LDEV = 0.26;
% Average_Distance_Traveled_P = 12000 % (Private_Vehicles)
Dist_T_LDEV = 12000;
% Total Energy Required (kWh) = Total Distance Traveled * kWh/mile for LDEV
Eng_T_LDEV = Dist_T_LDEV * Eng_LDEV;
% Cost of Electricity ($/kWH)
Cost_Electricity = 0.12;
% Total operating cost ($/year)
Opr_T_Cost_LDEV = Eng_T_LDEV * Cost_Electricity;
Cost_1_LDEV = (25000 + (Bat_Cost_LDEV) + (c_VA*P_c)); % Price of 1 light duty electric vehicle
% Total purchase cost ($)
Pur_T_Cost_LDEV = Cost_1_LDEV * 1;
% Battery change cost (once in every 10 years)
Bat_Cost_LDEV = Q_b_LDEV*c_b_LDEV*1;
% Maintenance Cost (2% of purchase cost every year)
Man_T_Cost_LDEV = (Pur_T_Cost_LDEV * 2/100);
% Total cost per year
TCPY_LDEV = Opr_T_Cost_LDEV + Man_T_Cost_LDEV;
% Total cost for 10 years
TC10Y_LDEV = 10*Opr_T_Cost_LDEV + 10*Man_T_Cost_LDEV;

% ICEV_gallon_per_mile #(gallon/mile)
Eng_LDICE = 0.033; % (30 miles/gallon)
% Average_Distance_Traveled_P = 12000 % (Private_Vehicles)
Dist_T_LDICE = 12000;
% Total Fuel Required (gallons) = Total Distance Traveled * gallon/mile for LDICE
Eng_T_LDICE = Dist_T_LDICE * Eng_LDICE;
% Cost of Fuel ($/gallon)
Cost_Fuel = 2.5;
% Total operating cost ($/year)
Opr_T_Cost_LDICE = Eng_T_LDICE * Cost_Fuel;
Cost_1_LDICE = 35000; % Price of 1 Light Duty ICE Vehicle
% Total purchase cost ($)
Pur_T_Cost_LDICE = Cost_1_LDICE * 1;
% Battery change cost (once in every 10 years = 40% of purchase cost)
% Maintenance Cost (4% of purchase cost every year)
Man_T_Cost_LDICE = (Pur_T_Cost_LDICE * 4/100);
% Total cost per year
TCPY_LDICE = Opr_T_Cost_LDICE + Man_T_Cost_LDICE;
% Total cost for 10 years
TC10Y_LDICE = 10*Opr_T_Cost_LDICE + 10*Man_T_Cost_LDICE;

Diff_Pur_Cost_LD = Pur_T_Cost_LDICE - Pur_T_Cost_LDEV;

Profit_Share = 0.75;
Net_Profit_LD = TCPY_LDICE - TCPY_LDEV;
Net_Profit = (Net_Profit_LD)*Profit_Share;

Results

% Generated by MATLAB on 30-Apr-2020 23:58:31
% MATLAB version: 9.6.0.1114505 (R2019a) Update 2
% ---------------------------------------------------------------------------

B_CPkWh = 300;
Bat_Cost_LDEV = 728.38827660476193;
C_rate_LDEV = 10.227272727272727;
Cost_1_LDEV = 27178.388276604761;
Cost_1_LDICE = 35000;
Cost_Electricity = 0.12;
Cost_Fuel = 2.5;
DeltaSOC = 20;
Diff_Pur_Cost_LD = 7821.6117233952391;
Dist_T_LDEV = 12000;
Dist_T_LDICE = 12000;
ER = 1;
E_c = 0.26;
Eng_LDEV = 0.26;
Eng_LDICE = 0.033;
Eng_T_LDEV = 3120;
Eng_T_LDICE = 396;
Man_T_Cost_LDEV = 543.56776553209522;
Man_T_Cost_LDICE = 1400;
N_evs = 20600;
N_lanes = 2;
N_pads = 1;
N_positions = 1;
Net_Profit = 1104.0241758509287;
Net_Profit_LD = 1472.0322344679048;
Opr_T_Cost_LDEV = 374.4;
Opr_T_Cost_LDICE = 990;
P_c = 50;
Profit_Share = 0.75;
Pur_T_Cost_LDEV = 27178.388276604761;
Pur_T_Cost_LDICE = 35000;
Q_b_LDEV = 4.4;
RM = 1;
TC10Y_LDEV = 9179.6776553209529;
TC10Y_LDICE = 23900;
TCPY_LDEV = 917.9677655320952;
TCPY_LDICE = 2390;
TCR_F = 6.235;
\[
\begin{align*}
c_{VA} &= 29; \\
c_{b\_LDEV} &= 165.54279013744588; \\
c_{e} &= 0.0273; \\
c_{g} &= 0.015; \\
c_{iD} &= 0.005; \\
c_{r} &= 1; \\
delta &= 1; 
\end{align*}
\]