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

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Introduction/Background:
- Need of Electrification
- Overview of Bus Electrification Project
- Overview and Limitations in Current Stationary Charging Technology
- Need of In-Motion Wireless Power Transfer
- Overview of Dynamic Wireless Power Transfer
- In-Motion WPT Techniques
- Comparison Inductive WPT vs Capacitive WPT
- GREET Model
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- Novel Contribution

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- Study II: Dynamic Wireless Power Transfer

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- Study II: Dynamic Wireless Power Transfer

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Acknowledgement

- **University Faculty:**
  - Dr. Zachary Asher
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  - Tushar Gaikwad
  - Amol Patil
  - Parth Kadav
  - Marsad Zoardar
Need of Electrification

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Air Pollution

CO₂ Regulation

Resources

Exhaust Regulation

Fuel Economy Regulation

Renewable Energy Source
Overview of Bus Electrification Project

- For a day operation, a transit bus may require a battery as large as 500 kWh
- Compared to energy storage by liquid fuel, batteries are expensive (300$/kWh) and heavy (10kg/kWh)
- 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
- Using fast chargers installed at depot or on route bus stops for charging the battery scheduled stop time
- 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
Overview & Limitations in Current Stationary Charging Technology

- From 2023 onward, all taxis in Oslo will be zero emission
- Current vision for most EV’s is stationary charging at charging stations
- Stationary WPT requires long recharging times
- High capital cost and High operating cost
- Limited range especially, in cold weather battery capacity is reduced
- Rather waiting for the perfect battery why not change the charging system?
- In-motion WPT is an exciting alternative
- In motion WPT system is less complex
Need of In-Motion Wireless Power Transfer

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ELECTRIC VEHICLES vs. INTERNAL COMBUSTION ENGINE VEHICLES

- Fuel Cost per 100 Gallons ($)
- Annual Maintenance Costs ($)
- CO2 Emissions (Grams/CO2/equivalent)

- Electric Vehicles
- Internal Combustion Engine Vehicles
**Inductive:**
- Uses magnetic field coupling between conducting coils
- High efficiency and high-power capability
- Adequate for short & medium distance high power delivery
- Bulky configuration and expensive
- Efficiency reduces due to misalignment
- Sensitivity to metal objects

**Capacitive:**
- Uses electric field coupling between conducting plates
- Can be operated at higher frequencies
- Reduced Sensitivity to misalignment
- Needs a huge area to transfer several kW Power
- Very small capacitance so effective power transfer occurs at very high frequencies
Comparison Inductive WPT vs Capacitive WPT

<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>Medium</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 we will study IPT in details
GREET Model

- Provides a consistent life-cycle analysis platform
- 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:
  1. WTP (Well-to-Pump)
  2. WTW (Well-to-Wheels)
  3. Data Editors
  4. Simulation Parameters
## Overview of Dynamic Wireless Power Transfer

### Introduction

<table>
<thead>
<tr>
<th>Researchers/Group</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ioannis Karakitsios, Foivos Palaiogiannis, Achilleas Markou [1]</td>
<td>Novel optimization procedure in order to maximize the energy transferred to an EV, at considerably high efficiency by a dynamic IPT system</td>
</tr>
<tr>
<td>Thomas Navidi, Yue Cao [2]</td>
<td>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</td>
</tr>
<tr>
<td>Thammasat University Rangsit Campus [3]</td>
<td>studied a new method for implementing, modeling, and measuring in-motion WPT for an EV charger also 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</td>
</tr>
<tr>
<td>Nikolay Madjarov, Aitor Bustillo [4]</td>
<td>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</td>
</tr>
<tr>
<td>Oak Ridge National Laboratory [5]</td>
<td>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 maximum power transferred measured in the lab was 4.2 kW with 92% transfer efficiency</td>
</tr>
<tr>
<td>Ahmed A. S. Mohamed; Christopher R. Lashway; Osama Mohammed [6]</td>
<td>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</td>
</tr>
<tr>
<td>Idaho National Laboratory [7]</td>
<td>Considerations for Corridor and Community DC Fast Charging Complex System Design and cost estimation</td>
</tr>
<tr>
<td>Rogge, Matthias, Sebastian Wollny, and Dirk Sauer [8]</td>
<td>Fast charging battery buses for the electrification of urban public transport it is a feasibility study focusing on charging infrastructure and energy storage requirements</td>
</tr>
<tr>
<td>Limb, Braden J., Zachary D. Asher, Thomas H. Bradley, Evan Sproul, David A. Trinko, Benjamin Crabb, Regan Zane, and Jason C. Quinn [9]</td>
<td>Economic Viability &amp; 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 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, &amp; vehicle technologies</td>
</tr>
</tbody>
</table>
Novel Contribution

- Developed and validated high-fidelity transit electric bus model
- Used MILP for estimating minimum cost by optimizing battery size and charging power
- Study II improves the understanding of environmental, economic, & implementation potential of In-Motion WPT
- Uses validated high-fidelity vehicle model for LDEV which have been absent from existing studies
- There are no studies that address the environmental, economic, and implementation potential of In-Motion WPT using validated high-fidelity vehicle models
- It combines the 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
Study I: Transit Bus Electrification Procedure

Create Drivetrain Model (Backward Looking)

Tune and Validate Model with Foothill Transit data

Run model on data logged from Zion National Park to estimate energy consumption

Draw Geofences around stops to estimate charging opportunity. Aggregate charging opportunity and energy use into 5min bins

Optimize fleet and charging infrastructure design with Linear Programming
Drivetrain Modelling

- A backward-looking vehicle drivetrain model was used to estimate energy consumption for each bus:
  - Battery
  - Motor
  - Transmission
  - Differential
  - Wheel
  - Chassis
  - Logged Data

- The model first calculates the road load on the vehicle:
  \[
  F_{\text{Road}} = m \frac{dv}{dt} + mgsin\theta + C_{\text{dl}}v^2 + mgC_{rr}
  \]

- 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.
Foothill Transit – Logged Data

- Line 291 has a fast charger
- Logged data includes mid-day charging at the Transit Center
- Fast charging events are characterized by current > 350A flowing into the battery & removed to calculate driving net energy
- Fig. show Bus charging at an On-Route Charger on line 291 and Energy Consumption in one day with On-Route charging
Foothill Transit – Simulated

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**Speed & Battery SOC**

Modeled Energy Consumption vs Measured Energy Consumption with On-Route Charging

Modeled Energy Consumption vs Measured Energy Consumption

Distance traveled in one day for one bus
Selected 10 vehicle days common to all 11 buses in the dataset

Those common days were selected for the simulation

Energy use was modeled for the selected days and compared to measured energy consumption results
Current events which are less than 350 A are considered (i.e. $I < 350A$)

Checked the model with different mass, drag coefficients and rolling resistance

Calculated Modeled vs Measured Energy Consumption for these parameters

Also plotted the Avg Speed, Avg Acceleration & Average Absolute Grade to check which parameters we can change

We increased 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
Models With Different Mass And Drag Coefficient For Accuracy

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**Modeled vs Measured Energy Consumption**

- **Mass = 12000, Drag = 1.617**

- **Modeled vs Measured Energy Consumption**
  - Mass = 13000, Drag = 1.617
Models With Different Mass And Drag Coefficient For Accuracy

Modeled vs Measured Energy Consumption
Mass = 13000, Drag = 2.156

Modeled vs Measured Energy Consumption
Mass = 11500, Drag = 1.617
Energy Consumption Calculation Results

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Average Acceleration [m/sec^2]

Average Speed [m/sec]
Fig. Motor Energy Electrical [kWh] vs Battery Energy [kWh]

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

- Calculated the auxiliary energy consumption with the data from Foothill transit
- Auxiliary energy consumption was added to traction energy consumption to get the total energy consumed by each bus on each day
- The Final Parameters chosen are shown in the table

<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^2/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>
Final Modeled vs Measured Energy Consumption with chosen parameters and adding Auxiliary Energy Consumption is shown in the above figure.
Model Calibration Results

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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 then out of 80 vehicle days 76 are within 15% deviation.

The average error in simulated vs logged energy consumption is 11.06 kWh.

<table>
<thead>
<tr>
<th>Deviation % (Within)</th>
<th>Number of 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 identify opportunities for electric vehicle charging along the bus route, a bus map from the park was consulted.

Geofences were drawn around each stop to classify dwell time.

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.

Fig shows 10 different zones in 10 different colors.

Zone 10 is bus depot which is shown in blue.
Daily Stop Time at Each Zone

Fig shows Stopped time in each zone for one day

- Visitor Center
- Museum
- Canyon Junction
- Court of the Patriarchs
- Zion Lodge
- The Grotto
- Weeping Rock
- Big Bend
- Temple of Sinawava
- Bus Depot
Optimization With Mixed-Integer Linear Programming

- Mixed-Integer Linear Programming used to find optimal number of chargers for the fleet depot & stops on-route

- Also to find an optimal set of vehicle battery sizes to minimize capital costs while replacing vehicles with their electrical equivalents

- The method has these objectives:
  1. Scheduling
  2. Battery and charger costs
  3. Personnel availability
  4. Shuttling
Vehicle Modelling & Optimization (Scenario I)

<table>
<thead>
<tr>
<th>Number of Buses</th>
<th>Number of Days of Operation</th>
<th>Battery Size (kWh)</th>
<th>Charger Size(kW) &amp; Location (Zone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>7</td>
<td>100 for 1 bus</td>
<td>75 at zone 5 (Zion Lodge)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>125 for 1 bus</td>
<td>75 at zone 9 (Temple of Sinawava)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 for 5 buses</td>
<td>50 at zone 10 (Bus Depot)</td>
</tr>
</tbody>
</table>
### Vehicle Modelling & Optimization (Scenario II)

<table>
<thead>
<tr>
<th>Number of Buses</th>
<th>Number of Days of Operation</th>
<th>Battery Size (kWh)</th>
<th>Charger Size (kW) &amp; Location (Zone)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17 (All)</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>

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Cost Modeling: 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)

Cost estimation for 1 charger 75 kW including all electronics, engineering, labor, infrastructure and charger has shown in the table [7]

Scenario I: Total Charging Infrastructure Cost = $227,000 + $101,000 = $328,000

<table>
<thead>
<tr>
<th>Parameter/Electronics</th>
<th>Cost 75 kW ($)</th>
<th>Cost 50 kW ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>$3,000</td>
<td>$3,000</td>
</tr>
<tr>
<td>Permit</td>
<td>$1,000</td>
<td>$1,000</td>
</tr>
<tr>
<td>Utility Interconnection Cost</td>
<td>$10,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Load Center and Meter Station</td>
<td>$2,000</td>
<td>$2,000</td>
</tr>
<tr>
<td>DCFC Unit Hardware</td>
<td>$37,500</td>
<td>$25,000</td>
</tr>
<tr>
<td>Conduit and Cables</td>
<td>$3,000</td>
<td>$3,000</td>
</tr>
<tr>
<td>Concrete Pads, Materials &amp; Labor</td>
<td>$5,000</td>
<td>$5,000</td>
</tr>
<tr>
<td>Accessory Material</td>
<td>$4,000</td>
<td>$4,000</td>
</tr>
<tr>
<td>Site Surface &amp; Underground Work</td>
<td>$13,000</td>
<td>$13,000</td>
</tr>
<tr>
<td>Fixed Site Improvements</td>
<td>$13,000</td>
<td>$13,000</td>
</tr>
<tr>
<td>Equipment Installation Cost</td>
<td>$12,000</td>
<td>$12,000</td>
</tr>
<tr>
<td>Project Management</td>
<td>$10,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Total</td>
<td>$113,500</td>
<td>$101,000</td>
</tr>
<tr>
<td>Number of Stations</td>
<td>x 2</td>
<td>x 1</td>
</tr>
<tr>
<td>Total for Two Stations</td>
<td>$227,000</td>
<td>$101,000</td>
</tr>
</tbody>
</table>
Cost Modeling: Cost of Charging Infrastructure (Scenario II)

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There will be two Chargers of 75 kW at zone 4 (Court of Patriarchs)

And two 25 kW charger at zone 9 (Temple of Sinawava)

Cost estimation chargers including all electronics, engineering, labor, and infrastructure charger has shown in the table [7]

<table>
<thead>
<tr>
<th>Parameter/Electronics</th>
<th>Cost 75 kW ($)</th>
<th>Cost 25 kW ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engineering</td>
<td>$3,000</td>
<td>$3,000</td>
</tr>
<tr>
<td>Permit</td>
<td>$1,000</td>
<td>$1,000</td>
</tr>
<tr>
<td>Utility Interconnection Cost</td>
<td>$10,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Load Center and Meter Station</td>
<td>$2,000</td>
<td>$2,000</td>
</tr>
<tr>
<td>DCFC Unit Hardware</td>
<td>$37,500 x 2</td>
<td>$12,500 x 2</td>
</tr>
<tr>
<td>Conduit and Cables</td>
<td>$3,000</td>
<td>$3,000</td>
</tr>
<tr>
<td>Concrete Pads, Materials &amp; Labor</td>
<td>$5,000</td>
<td>$5,000</td>
</tr>
<tr>
<td>Accessory Material</td>
<td>$4,000</td>
<td>$4,000</td>
</tr>
<tr>
<td>Site Surface &amp; Underground Work</td>
<td>$13,000</td>
<td>$13,000</td>
</tr>
<tr>
<td>Fixed Site Improvements</td>
<td>$13,000</td>
<td>$13,000</td>
</tr>
<tr>
<td>Equipment Installation Cost</td>
<td>$12,000</td>
<td>$12,000</td>
</tr>
<tr>
<td>Project Management</td>
<td>$10,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>Total</td>
<td>$151,000</td>
<td>$101,000</td>
</tr>
</tbody>
</table>

Scenario II: Total Charging Infrastructure Cost = $151,000 + $101,000 = $252,000
## 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 Per Year $</td>
<td>37600</td>
</tr>
</tbody>
</table>

## 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 Per Year $</td>
<td>8109.92</td>
</tr>
</tbody>
</table>
## Cost Modeling: Purchase Cost & Profit

### Vehicle Purchase Including Battery Cost

<table>
<thead>
<tr>
<th></th>
<th>Total Vehicle Purchase Cost</th>
<th>Battery Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Vehicle Purchase Cost</strong> (Scenario I)</td>
<td>$1,757,000</td>
<td>Cost of Battery ($/kWh)</td>
</tr>
<tr>
<td><strong>Total Vehicle Purchase Cost</strong> (Scenario II)</td>
<td>$4,139,500</td>
<td>Battery Size 1 (kWh)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Battery Size 2 (kWh)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Battery Size 3 (kWh)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total cost of Battery 1 ($)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total cost of Battery 2 ($)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total Cost of Battery 3 ($)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total number of buses (Scenario I)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total number of buses (Scenario II)</td>
</tr>
</tbody>
</table>

### Battery Cost

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

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Cost Estimation: Payback Period

- Finally the Payback Period is calculated with the following formula

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

<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>
Emissions Results for Bus (GREET)

### Emissions I

<table>
<thead>
<tr>
<th></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>

### Emissions II

<table>
<thead>
<tr>
<th></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>

---

*Western Michigan University* Energy Efficient & Autonomous Vehicles Laboratory
Emissions Results for Bus (GREET)

### Introduction

### Methodology

#### Study I

#### Results Study I

#### Methodology

#### Study II

#### Results Study II

#### Conclusion & Future Work

### Emissions III

<table>
<thead>
<tr>
<th></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>

### Emissions IV

<table>
<thead>
<tr>
<th></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>

---

**Table 1:** Emissions Results for Bus (GREET) - Study I

**Table 2:** Emissions Results for Bus (GREET) - Study II

**Table 3:** Emissions Results for Bus (GREET) - Conclusion & Future Work

***Legend***:
- **Electricity (kg/mi)**
- **Diesel (kg/mi)**
- **Propane (kg/mi)**
Energy Use Results for Bus (GREET)

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

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Methodology
Study II
Results Study II
Conclusion & Future Work
Study II: Dynamic Wireless Power Transfer Procedure

**Project Tasks:**
- Develop Validated Vehicle Models
- Add Inductive vs. Capacitive In-Motion WPT Model
- Add Emissions from Geographic Energy Sources Model
- Add Economic Cost and Savings Model from In-Motion WPT

**Introduction**

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**Results Study I**

**Methodology**

**Results Study II**

**Conclusion & Future Work**
To obtain signals for drive input, a driving vehicle equipped with different sensors such as GPS, CAN data logger, and radar

- It 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
- It is important to note that the timestep used for the analysis is 0.1 seconds
Concept of In-Motion WPT

ROAD STRUCTURE

Primary Side
- WPT Pads
- Compensation Network
- DC/ HF AC Converter
- Energy Management System
- AC/DC Converter
- Battery
- Drive Motor
- Electricity from Grid

Secondary Side
- Compensation Network
- AC/DC Converter

POWER TRANSFER SYSTEM

VEHICLE

VEHICLE Primary Side
- Compensation Network
- AC/DC Converter
- Energy Management System
- Battery
- Drive Motor

VEHICLE Secondary Side
- Compensation Network
A high-fidelity backward-looking electric drivetrain model for Light Duty Electric Vehicle is developed in python.

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.

<table>
<thead>
<tr>
<th>Vehicle Mass</th>
<th>1580.87 kg</th>
</tr>
</thead>
<tbody>
<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>

<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>
A backward-looking drivetrain model has been created

Tuned and validated model with the data from route in Fort Collins, Colorado
Energy Consumption Calculation

Case I: Toyota Prius Prime (2017 Model)

- 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 1.024 kWh without auxiliary energy consumption
- So, it uses 0.26 kWh/mile energy

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

![SOC Profile for Toyota Prius Prime](image2)
Energy Consumption Calculation

Case II: Toyota Prius Plug-In Hybrid (2010 Model)

- 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 1.024 kWh without auxiliary energy consumption
- So, it uses 0.26 kWh/mile energy

Energy Consumption for Toyota Prius Plug-In Hybrid

SOC Profile for Toyota Prius Plug-In Hybrid
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.

<table>
<thead>
<tr>
<th>General Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC Bus Voltage [V]</td>
<td>89</td>
</tr>
<tr>
<td>Frequency [Hz]</td>
<td>25,740</td>
</tr>
<tr>
<td>IGBT Duty Cycle [%]</td>
<td>50</td>
</tr>
<tr>
<td>Series Inductance (LPs)[μH]</td>
<td>70</td>
</tr>
<tr>
<td>Series Resistance (RPs) [mΩ]</td>
<td>0.125</td>
</tr>
<tr>
<td>Primary Parallel Capacitance (CPP) [mF]</td>
<td>2</td>
</tr>
<tr>
<td>Secondary Parallel Capacitance (CSP) [mF]</td>
<td>0.23</td>
</tr>
<tr>
<td>Load Resistance (R) [Ω]</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Transformer**

- Primary Self-inductance [μH]: 100
- Secondary Self-inductance [μH]: 350
- Coupling Coefficient [-]: 0.62
As we got an IPT model ready with 50kW mean output power we can incorporate that IPT model to the electric drivetrain model.

To see the results for vehicle charging when it is driving the route in Fort Collins, 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%.

Checked the final State of Charge for each scenario after completing the one drive instance.
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:
1. GHG emissions (CO$_2$, CH$_4$, N$_2$O, and total CO$_{2e}$)
2. Energy use (total, fossil petroleum, coal, natural and renewable energy)
3. Emissions of criteria pollutants (VOC, CO, NO$_x$, PM$_{10}$, PM$_{2.5}$, and SO$_x$)

We have considered 12000 vehicle miles traveled by a light duty electric vehicle throughout the year.

Then compared the emission results from electric vehicles (WTW) with conventional vehicle emissions results.

The results showed that the CO2 emission as well as GHG emissions were much lesser in electric vehicles.
Cost Estimation

- The cost model consists of the infrastructure cost parameters are shown in the table above [6].
- It also discusses 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.
- Then calculated the profit by replacing the conventional vehicle with the reduced battery sized electric vehicle.
The results from the IPT Configuration has shown in the figures:

- First figure shows the Input Voltage and Input Current
- And the second figure shows the Output Voltage and Output Current
Results from IPT Configuration: Output Power & Efficiency

- 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%
SOC Results: Scenario I Prius Prime

- Charging Power = 50 kW
- Battery Size = 8.8 kWh
- Starting Initial SOC= 23%
- Considered different cases of road electrification from 50% to 100%

<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>
The State of Charge (SOC) level was 23% at the start of the drive cycle and it ends at 11.19% after driving the route without DWPT.

On 100% electrification after driving the wireless power transfer route, the final SOC reads 45.74%.

Whereas for 50% road coverage, the SOC shows a reading of 20.88%.

As the road coverage percentage increases, the final SOC level after the end of the drive cycle increases.

That means on 100% electrification of a 4-mile route, it charges to its maximum level at the end of the drive cycle.
SOC Results: Scenario I Prius Plug-In Hybrid

- Charging Power = 50 kW
- Battery Size = 4.4 kWh
- Starting Initial SOC= 35%
- Considered different cases of road electrification from 50% to 100%

<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>
The State of Charge (SOC) level was 35% at the start of the drive cycle and it ends at 11.39% after driving the route without DWPT.

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%.

As the road coverage percentage increases the final SOC level after the end of the drive cycle increases.

That means on 100% electrification of 4-mile route charges to maximum level at the end of drive cycle.
Emission Results

<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>

**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>
# Emission Results

<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>

<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>
Cost Estimation Results

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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>

Profit ($) $1466.89
Share Towards Infrastructure ($) $366.72
Net Profit ($) $1100.17

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>

Profit ($) $1472.03
Share Towards Infrastructure ($) $368
Net Profit ($) $1104.03

- The road retrofitting cost including power electronics and WPT components is M$3.1175 per mile per lanes
- We found that the operational and maintenance cost for electric vehicles is much lesser than conventional vehicles
- The profit is calculated after giving certain amount of money towards infrastructure cost to recover that money
- 25 percent of the profit share is contributed towards the infrastructure cost
Summary (Study I)

- An operationally feasible system to replace conventional buses with their battery-electric equivalents is designed by:
  1. Calibrating Electric Bus Drivetrain Model
  2. Identifying charging opportunities
  3. Optimizing the charging operations to minimize operating costs

- A calibrated BEB model, geo-fencing, & linear programming 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

- Mixed-Integer Linear Programming is used to find an optimal charging strategy

- The detailed economic analysis has been done, also, Calculated the payback period for whole system
Simulink model for IPT has been studied, different combinations are developed.

Capacitive WPT is also a great alternative as expected results suggest.

GREET model studied and calculated the emissions & energy use.

Capacitive and Inductive WPT have great potential to improve transportation sustainability.

Economic Analysis has been done for LDEV.

High fidelity modelling of EV has been developed.
Conclusion

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
- 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
- Dynamic Wireless Power Transfer (DWPT) is solution for the range anxiety in Light Duty Electric Vehicles
- 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

**Overall Conclusion**

- 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 initial research we can say that Transit Bus Electrification & In-Motion WPT is very economic, eco-friendly & efficient technique for transportation
Future Work

Study I
- 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
- Also, Study additional datasets are available for shuttles operating within the national parks system

Study II
- 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
- Study different vehicle models and to different vehicle types including the heavy-duty vehicles for DWPT
- Incorporate different power levels and study its effects on the battery size & road electrification percentage
Thank You!
Pros/Cons of In-Motion Wireless Power Transfer

**Pros of In-Motion WPT**
- Cheaper Electric Vehicle
- Smaller battery size
- Energy Efficiency
- Extended driving range & reduces concerns of range anxiety
- Reduced emissions

**Cons of In-Motion WPT**
- Expensive Infrastructure
- Implementation Scope: Urban Environment Long Distance
The following table explains about the GREET Terminologies in brief:

<table>
<thead>
<tr>
<th>Terminology</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>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.</td>
</tr>
<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>
Data For Simulation

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Fig. One day Energy Consumption for one of the common days

Fig. One day Energy Consumption for 2nd common day
Transit Bus Electrification

There are two different methods for charging the transit electric buses

1. **Standard charging**
   - It is a charging with moderate charging power usually overnight charging in the bus depot or during longer breaks
   - This causes a higher battery capacity & higher weight of the system, when the bus shall be operated the entire day

2. **Fast Charging**
   - It 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 the track during operation reduces battery capacity and furthermore the weight significantly
   - However, bus schedule must provide sufficient charging time at certain locations
Transit Bus Electrification

The simulation is divided in 3 different steps:

1. **Energy Consumption**
   - The energy consumption of each trip is simulated based on the defined bus type and the geographical characteristics of the bus route

2. **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 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

3. **Battery Capacity**
   - The required battery capacity is calculated for each bus route based on the given charging power
Models With Different Mass And Drag Coefficient For Accuracy

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- **Methodology Study II**
- **Results Study II**
- **Conclusion & Future Work**

After comparing modeled vs measured energy consumption it was not as expected. We thought to change some parameters to get the accurate results. Checked the model with different mass, drag coefficients and rolling resistance. Some of those results are shown. The parameters are chosen which gave the best results.
Energy Consumption Calculation Results

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% Deviation

Absolute Grade

Measured Consumption [kWh]

Modeled Consumption [kWh]

Deviatio (%) vs. Measured Consumption [kWh]

Deviatio (%) vs. Modeled Consumption [kWh]

Average Grade vs. Measured Consumption [kWh]

Average Grade vs. Modeled Consumption [kWh]
Model Calibration Results

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% Deviation

Average Speed [m/sec]
Model Calibration Results

Average Acceleration [m/sec^2]  Absolute Grade
# Solver Parameters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Type</th>
<th>Dimensions</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\psi_b$</td>
<td>Cost of Battery Capacity, $$/kWh$</td>
<td>Param</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>$\psi_c$</td>
<td>Unit cost of Chargers $$/charger$</td>
<td>Param</td>
<td>1</td>
<td>10000</td>
</tr>
<tr>
<td>$\psi_z$</td>
<td>Cost of Shuttling Buses $$/move$</td>
<td>Param</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>$E_b$</td>
<td>Battery Energy Consumption</td>
<td>Input</td>
<td>$n_v \times n_t$</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>Charge Opportunity, hr</td>
<td>Input</td>
<td>$n_v \times n_t \times n_z$</td>
<td>$0 - \frac{1}{12}$</td>
</tr>
<tr>
<td>$P$</td>
<td>Availability of Personnel</td>
<td>Input</td>
<td>$n_t$</td>
<td>0-1</td>
</tr>
<tr>
<td>$Y$</td>
<td>Charging Power</td>
<td>Var</td>
<td>$n_v \times n_t \times n_z$</td>
<td>-</td>
</tr>
<tr>
<td>$S$</td>
<td>Charging Switch</td>
<td>Var</td>
<td>$n_v \times n_t$</td>
<td>0-1</td>
</tr>
<tr>
<td>$N_c$</td>
<td>Number of Chargers</td>
<td>Var</td>
<td>1</td>
<td>0-10</td>
</tr>
<tr>
<td>$C$</td>
<td>Battery Sizes</td>
<td>Var</td>
<td>$n_v$</td>
<td>0-500</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Charging State</td>
<td>Var</td>
<td>$n_v \times n_t \times n_z$</td>
<td>0-1</td>
</tr>
</tbody>
</table>
Different Combinations for Inductive WPT Model
High Efficiency Inductive WPT

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Graphs showing data trends over time.