Economic Viability and Environmental Impact of In-Motion Wireless Power Transfer

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Abstract—In-motion charging of electric vehicles (EVs) using wireless power transfer (WPT) represents an alternative to both traditional internal combustion engine (ICE) transportation and long-range EVs. This study focuses on understanding the economics, environmental impact, and infrastructure rollout of in-motion WPT applied to the U.S. transportation fleet. The work represents a novel, large-scale integration of numerous research methodologies previously presented by our research group into a comprehensive study to thoroughly address potential in-motion WPT implementation scenarios using geographically-diverse datasets, validated vehicle models, real-world drive cycles, variable vehicle adoption rates, and variable infrastructure deployment rates. By using both in-motion WPT and conventional charging infrastructure, the proposed vehicle and roadway architectures satisfy 97.7% of the sampled 24-hour drive cycles, a 22.4% increase over a baseline short range EV without in-motion charging. Economic results show a national return on investment but economic viability is dramatically impacted by up-front capital costs and technology adoption. An environmental impact assessment shows that total GHG emissions from light duty vehicles and Class 8 trucks would be reduced by 29.3 trillion kg CO₂-eq. (30.6%) when compared to a business as usual scenario (i.e. a scenario were current overall emissions trends continue) for the first 50 years of technology deployment. These results demonstrate that in-motion charging using WPT presents both economic and environmental benefits when compared to conventional ICE transportation and a long-range EV fleet.

Index Terms—Electric Vehicle, Battery, Electrification, Transportation, Techno-economic Analysis, Life Cycle Assessment, Environmental Impact Assessment

I. INTRODUCTION

Transportation is a primary consumer of energy in the US [1]. The improved performance of electrical energy storage and conversion systems has resulted in the commercialization of a variety of electrified vehicles including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and fully electric vehicles (EVs) [2–5]. But, consumer adoption of EVs has been limited due to their restricted range, long recharging times, and higher total purchase price compared to traditional internal combustion engine (ICE) vehicles [2, 5–8]. EV designs that seek to improve their range, and thereby improve their consumer acceptability have focused on integrating large onboard battery systems and high-speed charging infrastructure despite the high cost and excess mass implications of these technologies [6, 8, 9]. A new solution to these issues is technology known as in-motion wireless power transfer (WPT), dynamic charging, or charging while driving (CWD). This technology can be a means to improve the range, consumer acceptability, and costs of EVs without requiring the integration of large capacity batteries as has
been stated in overall system operation reviews [10–12], technology reviews [9, 13–15], and new reviews published in just the last two years [16–21]. By using this technology, the battery capacity of the EV could be downsized, while improving the range and utility of the EV.

Because of the potential benefits of in-motion WPT, numerous research programs are dedicated to the realization of in-motion WPT by focusing on aspects such as driving range [22], energy transmission efficiency considerations [23, 24], weather considerations [25], overall system design [26–31], physical vehicle implementation [32–34], infrastructure implications [35–38], and investigating traffic implications [39–42].

But, few researchers are investigating life cycle environmental and techno-economic considerations of in-motion WPT. One example result is a demonstration of WPT buses that can be less expensive to operate than stationary charging EVs [43], with large reductions in fuel costs (∼80% reduction) compared to diesel buses [44]. Environmental studies have shown WPT can realize environmental benefits compared to traditional transportation systems [44–46]. In more general, large-scale, and fleet-wide applications, in-motion WPT has been demonstrated to realize economic benefits characterizable as a national return on investment (ROI) of between 5-12 years [46–49].

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 a in-motion WPT fleet in the U.S. with sensitivity considerations, a scope that has not been adequately addressed by previous research. Our research group began filling this gap in 2015 with some initial environmental improvement results [46, 48], initial regional results [47], and most recently initial Class 8 truck focused results [50], all of which have been presented as short conference or workshop papers. The work represents a novel, large-scale integration of each of these pieces into a comprehensive study to thoroughly address potential in-motion WPT implementation scenarios using geographically-diverse datasets, validated vehicle models, real-world drive cycles, variable vehicle adoption rates, and variable infrastructure deployment rates. To enable this type of large scale assessment, this work includes comprehensive dynamic vehicle energy consumption models integrated with second-by-second real-world drive cycles, variable vehicle adoption and infrastructure deployment rates, as well as Geographic Information Systems (GIS)-based infrastructure locating to evaluate and enable networks of in-motion WPT. Infrastructure rollout and vehicle modeling are integrated with economic and environmental models to understand the costs and benefits of in-motion WPT for transportation in the U.S.

II. Methods

Evaluation of a proposed in-motion WPT system requires concurrent modeling of both the in-motion WPT infrastructure and the vehicle. Descriptions of the vehicle model, WPT technology modeling, economic modeling, and environmental assessment are presented in the following sections.

A. Vehicle Modeling

Vehicle models were developed for both light-duty vehicles and Class 8 trucks, which together represent 94% of vehicle miles traveled in the U.S. [51]. Additionally, for both of these vehicle types, representative ICE vehicle models and WPT EV models were developed for multiple vehicle standards such as mid-size, compact, etc.

The ICE vehicle models were adapted to represent light duty vehicles and Class 8 trucks that are representative of current U.S. vehicles. The ICE powertrain model is representative of a conventional modern powertrain, model details are shown in Appendix A. It includes a gasoline-powered engine mated to a 6-speed transmission for the light duty vehicle models and a general diesel powertrain for the Class 8 truck models. Vehicle specifications were selected such that the combined UDDS/HWFET fuel economy of the modeled ICE vehicles was equal to the US average vehicle at 21.4 mpg (11.0 L/100km) for light duty vehicles.
TABLE I: An example ICE and WPT vehicle model specifications for one vehicle standard.

<table>
<thead>
<tr>
<th>Parameter Name</th>
<th>Light Duty ICE</th>
<th>Class 8 Truck ICE</th>
<th>Light Duty WPT</th>
<th>Class 8 Truck WPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Mass (kg)</td>
<td>2,072</td>
<td>20,000</td>
<td>1,498</td>
<td>20,000</td>
</tr>
<tr>
<td>Tire Diameter (m)</td>
<td>0.81</td>
<td>1.04</td>
<td>0.63</td>
<td>1.04</td>
</tr>
<tr>
<td>Frontal Area (m²)</td>
<td>2.23</td>
<td>10</td>
<td>2.30</td>
<td>10</td>
</tr>
<tr>
<td>Maximum Engine Torque (Nm)</td>
<td>303</td>
<td>2,000</td>
<td>280</td>
<td>2,500</td>
</tr>
<tr>
<td>Drag Coefficient</td>
<td>0.4</td>
<td>0.6</td>
<td>0.28</td>
<td>0.6</td>
</tr>
<tr>
<td>Driveline Efficiency</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>Rolling Coefficient</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
<td>0.008</td>
</tr>
</tbody>
</table>

and 5.8 mpg (40.6 L/100 km) for Class 8 trucks [52]. Vehicle parameter specifications from one light-duty and Class 8 ICE vehicle standard is shown in Table I. A direct comparison of simulated and current energy consumption for the ICE light duty vehicles and Class 8 trucks was performed to provide model verification. The light duty ICE was within 1.3% (0.3 MPG) and 2.8% (0.5 MPG) for the Highway Fuel Economy Test (HWFET) and Urban Dynamometer Driving Schedule (UDDS), respectively. The ICE Class 8 truck was within 0.6% (0.04 MPG) and 4.5% (0.2 MPG) for HWFET and UDDS 28 drive cycles, respectively.

Once verified, vehicle dimensions from the ICE models were used in the WPT EV models with the required energy management systems (WPT and supercapacitors) and drivetrain. The WPT EV model includes a battery for energy storage, a motor/generator connected to a fixed gear ratio transmission, and a WPT system for receiving power. To enable high-rate WPT, both the light-duty and Class 8 EVs incorporate a supercapacitor system in addition to its lithium-ion battery [53–55]. WPT charges the supercapacitor directly and thus the WPT rate is limited based on SOC of the capacitor system. Class 8 trucks can support multiple WPT receiving pads and thus WPT infrastructure is most constrained by the design characteristics of the light duty vehicle fleet. The longer length of Class 8 trucks can support 5 receiving pads which is necessary to compensate for the 4.8x energy consumption increase for these vehicles when compared to light-duty vehicles. This 4.8x energy consumption increase was determined by comparing the energy consumption from the light-duty and Class 8 vehicle models. The efficiency of WPT from the grid to the battery was modeled at 83% which is consistent with previous research [56–58] when accounting for misalignment and other factors but is conservative compared to modern systems that are capable of operating in the 92-94% efficiency range for well-aligned instances [59]. Note that this energy loss is accounted for in fueling costs (e.g. cost paid by the consumer) in the economic model as discussed in Section II-B2. Control of the capacitor discharge rates limits battery charging to 2C which is consistent with existing research establishing that this rate ensures normal battery life [60, 61]. Regenerative braking allows for the recapture of vehicle kinetic energy during braking. Stationary charging is assumed to be ubiquitous and to occur at any location where the EV stops for more than 1 hour. No change in speed or driver behavior is required to accomplish this notional in-motion WPT. The performance of these vehicles was scaled such that both the WPT EVs and the ICE vehicles have the same 0-60 mph (0-102 kph) time. Vehicle parameter specifications from one light-duty and Class 8 WPT vehicle standard is shown in Table I.

B. Infrastructure and Vehicle Design

This study seeks to concurrently evaluate a range of infrastructure and vehicle designs so as to understand the costs and benefits of in-motion WPT in the US. The infrastructure of in-motion WPT and stationary chargers is characterized by
the power of WPT charging that is installed on US roadways (between 25 kW and 100 kW were considered), and the power of stationary charging infrastructure (between 1C and 3C was considered). The WPT-enabled vehicle designs are characterized by the EV range of the vehicles (between 0 mi and 300 mi (483km) were considered). This analysis was completed to find a suitable vehicle architecture for in-motion WPT. A summary table of these ranges is shown in Appendix A, Table III.

The WPT coverage on vehicle roadways is implemented on a per-lane, per-mile basis where coverage for that lane and mile is continuous for the specified power level which corresponds to evenly spaced WPT pads. A diagram of the proposed system is shown in Appendix A, Fig. 8.

By evaluating the design space of WPT-enabled vehicles and their associated infrastructure, we seek to compare tradeoffs among in-motion WPT infrastructure and vehicle characteristics. The notional in-motion WPT infrastructure and vehicle designs proposed in this study are evaluated using three key performance metrics presented in the following section.

1) Evaluation of the fraction of US driving met by in-motion WPT:

The first metric is the fraction of U.S. simulated driving that can be met in the long-term using 50 kW in-motion WPT vehicles and infrastructure [62]. Drive cycles are achieved if there is sufficient energy in the battery at all points in the drive cycle. This is an important consideration because the vehicles are frequently operating on roadways that are not equipped with WPT. Note that for drive cycles that are very short, we still assume that if the vehicle is on a WPT roadway, they are using the WPT system. It may be the case that those vehicles may replace all battery charge using stationary charging despite the inconvenience because it has a lower cost, but fully understanding that tradeoff would require a consumer preference study which is outside of the scope of this work and is anticipated to have a minimal impact.

To evaluate this metric we modeled the energy consumption and associated battery SOC of the in-motion WPT EVs on a second by second basis as they traverse geographically-specific longitudinal real-world drive cycles, geographically-specific in-motion WPT infrastructure, and notional stationary charging infrastructure. A 24-hour drive cycle was satisfied if the WPT-enable EVs SOC remained above 0% throughout the drive cycle. If, at any point, the vehicles SOC fell below 0%, the drive cycle was not satisfied by that particular WPT-vehicle dyad. Note that current hybrid electric vehicles and plug-in hybrid electric vehicles reserve some battery SOC for continued overall charge sustaining operation, typically around 10% [63]. But for future in-motion WPT vehicles that would exist in an environment of improved connectivity and battery SOC estimations there is no operational reason to leave a reserve of battery SOC, despite that there is a degraded performance when SOC<5% [64]. If this limit were increased and the battery size was kept the same, the drive cycle satisfaction would slightly decrease.

Longitudinal drive cycle data from 6 geographically diverse locations across the U.S. (California; Southern California; Atlanta, GA; Chicago, IL; Kansas City, MO; and Texas) was gathered from the National Renewable Energy Laboratorys (NRELs) Transportation Secure Data Center (TSDC) which includes light-duty vehicle drive cycles as well as Class 8 truck drive cycles [50, 62]. Class 8 trucks cannot achieve the same drive cycles that light-duty vehicles can due to their slower acceleration and in general there are significant differences between light-duty vehicle drive cycles and Class 8 truck drive cycles. Each GPS-tagged drive cycle in the database was referenced to its roadway locations and classifications (primary, secondary, local, etc.) as determined through the United States Census Bureaus Topologically Integrated Geographic Encoding and Referencing (TIGER) database. The result was a sample set of 17,636 geographically-specific 24-hour duration drive cycles derived from 6,254 instrumented vehicles. An example of three of the drive cycles from this dataset are shown in Fig. 1.
Fig. 1: Three random day-long drive cycles used in this study showing different driving behavior from the Austin region (a), the Atlanta region (b), the LA region (c).

2) Evaluation of infrastructure and fueling cost of in-motion WPT:

The second metric is the capital and operating costs of the in-motion WPT vehicles and infrastructure. To evaluate this metric, we calculate the incremental costs of the WPT EV infrastructure and operating costs over a 25 year time horizon.

Light duty ICE vehicle and Class 8 truck purchase prices were set at $34,372 and $150,000, respectively, corresponding to the average purchase price of vehicles in September 2016 [65]. Literature has shown that WPT EVs allow for a large reduction in battery size compared to traditional EVs resulting in lower purchase costs, therefore the purchase price of both light duty and Class 8 truck WPT EVs was set at 30% cheaper than its ICE counterpart which is consistent with previous research [56, 66]. The cost of batteries are $230 per kWh, the cost of the wireless pads are $40 per kW of WPT power, and the cost of the super capacitors are $2,400 per kWh based on previous research [67, 68]. Note that a $40 per kW of WPT power for the wireless pads is conservative when accounting for just pad material but assumes significant reduction in cost if this number is to include the compensation network and power electronics. Also note that all of these costs are incorporated in the model and the supercapacitor cost is much higher than the battery cost. Modeled vehicles were driven an average annual vehicle distance of 11,287 mi/year (18,165 km/year) for light duty vehicles and 65,897 mi/year (106,052 km/year) for Class 8 trucks [51]. Energy transfer efficiency losses for in-motion WPT are incorporated into vehicle fueling costs (paid for by the consumer) in the proposed model. All vehicles are replaced after their 15 year life [69] has elapsed. Batteries are assumed to last the life of the vehicle based on the slow charge rate which corresponds to long lifetime [70].

The baseline cost for retrofitting roadways with WPT used is $2.5 million per lane per mile which can deliver a continuous 50kW from the evenly spaced WPT pads and is consistent with previous research [71]. A detailed breakdown of this cost can be found in Appendix A, Table IV. But, this $2.5 million per lane per mile is subjected to a sensitivity analysis to incorporate additional technical designs making the cost used in the model $2.5 million ± $1 million per lane per mile. Note that the range of $2.5 ± $1 million encompasses the technical systems being developed today. Four examples include the On-Line Electric Vehicle (OLEV) inductive wireless system which is currently priced at $1.7 million per lane per mile [43, 72], the Primove Bombardier inductive power system which costs $7 million per lane per mile but this high power only requires 35% coverage which works out to $2.45 million per lane per mile [73, 74], the Siemens e-Highway conductive overhead line system which costs $2.1 million per lane per mile [75], and lastly the Utah State University system which is currently estimated
at $3.8 million per lane per mile but only requires 50% coverage which works out to $1.9 million per lane per mile effectively. This research is intended to provide life cycle environmental and economic analysis for all of these technical configurations thus the range of $2.5 \pm 1$ million per lane per mile is used. In general, this cost is based on retrofitting existing roadways and includes WPT electronics (40%), electric grid power delivery and infrastructure (10%), and resurfacing (50%). Maintenance costs associated with this system are estimated to be equivalent to the maintenance costs of conventional roadways which is consistent with previous research [11, 43, 76–78]. Note that scenarios assuming different payers for the infrastructure cost are not anticipated to significantly change the payback/recovery analysis and instead an analysis of relevant profitability can be shown.

Operation and maintenance costs are the sum of fueling/charging costs and maintenance. The cost of energy under the U.S. Energy Information Administration’s short term energy outlook for each region was used to define the gasoline and electricity cost for each US state [79]. Over the life of the analysis, gasoline prices are modeled to increase at 1.7% per year for 25 years, and electricity prices are modeled to increase at 0.2% per year for 25 years [80]. Maintenance costs of ICE and EVs were set at 4% and 2% of the purchase price per year, respectively, for all vehicle classes [81, 82]. Vehicle-level costs are then scaled to a national level using the average vehicle miles traveled per classification of roadway in each state.

3) Evaluation of environmental costs and benefits:

The last metric of interest is the environmental costs and benefits of the in-motion WPT fleet. The well-to-wheels environmental impacts of the conventional ICE and in-motion WPT vehicles are evaluated using Argonne National Laboratory’s Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model using the energy consumption results from vehicle modeling. Energy and emissions impacts of vehicle manufacturing and electrified roadway construction are excluded from this analysis. The emissions intensity of the electric grid is assumed unchanged over the lifetime of this study (continuing the current trends in decreasing the emissions intensity of the grid would further benefit the in-motion WPT EV in comparison to ICE vehicles). Greenhouse gas emissions of electricity are used based on the North American Electric Reliability Council (NERC) region in which the WPT charging load occurs. Greenhouse gas emissions of gasoline assume conventional reformulated gasoline without modeling of regional or seasonal differences. Environmental costs and benefits are presented using metrics of greenhouse gas (GHG) emissions, and the criteria pollutants VOC, CO, NO\(_x\), PM\(_{2.5}\), PM\(_{10}\), and SO\(_x\). The role of future restrictions on pollutants were not considered, Hazardous Air Pollutants Maximum Achievable Control Technology (HAPs MACT) regulations, California AB32, and other similar policies.

C. Infrastructure Rollout Scenario

A notional infrastructure rollout plan shown in Fig. 2 with a deployment at 13,788 miles per year is proposed to understand the long-term dynamics of in-motion WPT infrastructure construction, vehicle fleet adoption, and environmental benefits. In-motion WPT infrastructure is assumed to be deployed at a rate of 13,788 electrified roadway miles (22,190 km) per year (equal to the average number of centerline miles of new roads built per year from 2000 to 2013 in the U.S. [83]), but this value was also subjected to a sensitivity analysis. WPT rollout was prioritized so that “primary” roadways (e.g. interstate and other freeways, and expressways) were retrofitted with in-motion WPT hardware first. Only when all primary roadways were completed is retrofitting of “secondary” roadways (other principal arterial and minor arterial) begun [84, 85]. Local roads and secondary roadways of less than 30 mph (48 kph) speed limit are not retrofitted under the proposed scenarios of this study. Note that Fig. 2 shows the primary roadways electrified within the first five years and the secondary roadways are electrified
starting in year five.

In all vehicle classes, WPT vehicle sales are modeled to increase at a rate of 10% per year, and the number of new vehicles purchased is modeled at 7.2% of registered vehicles [86, 87]. The size and vehicle class breakdown of the U.S. vehicle fleet is unchanged over the scenario period in the model.

III. RESULTS

Results analyzing the fraction of US driving met by in-motion WPT, infrastructure and fueling costs, as well as environmental costs and benefits are presented in the following sections.

A. Fraction of US driving met by in-motion WPT in light duty vehicles and Class 8 trucks

Using the sample of geographically-realized longitudinal driving traces and the second-by-second models of vehicle energy consumption and battery SOC, we can model the fraction of U.S. driving that could be enabled under the baseline infrastructure rollout scenario. The results are presented on a TSDC-database-specific basis in Table II. The results for light-duty vehicles and Class 8 trucks broken out individually exhibited the same overall trend.

First, the results without in-motion WPT are considered. For EVs with a very small 25 mi (40 km) range, the vehicle is only able to meet the 24-hour energy demands of the drive cycle for between 70.5%-86.3% of the driving samples. This implies that between 29.5% and 13.7% of the daily driving samples cannot be met by such a low-range EV. For EVs with a 300 mi (483 km) range, the vehicle is able to meet the 24-hour energy demands of the drive cycle for between 99.4% and 100% of the driving samples. Only small fractions of the daily driving samples cannot be met by this long-range EV.

Comparing these results to the results for vehicles that can
TABLE II: Results of the TSDC study showing the percent of drive cycles satisfied with a 25 mile (40 km) range EV, a 300 mile (483 km) range EV, and a 25 mile (40 km) range EV with in-motion WPT.

<table>
<thead>
<tr>
<th>Study Region</th>
<th>25mi (40km)</th>
<th>300mi (483km)</th>
<th>25mi (40km) WPT</th>
<th>Total Cycles Analyzed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlanta</td>
<td>70.5%</td>
<td>99.4%</td>
<td>98.9%</td>
<td>8,586</td>
</tr>
<tr>
<td>California</td>
<td>75.1%</td>
<td>99.6%</td>
<td>93.0%</td>
<td>3,255</td>
</tr>
<tr>
<td>Chicago</td>
<td>79.9%</td>
<td>99.8%</td>
<td>99.3%</td>
<td>1,625</td>
</tr>
<tr>
<td>Kansas City</td>
<td>73.6%</td>
<td>100%</td>
<td>98.9%</td>
<td>360</td>
</tr>
<tr>
<td>Texas</td>
<td>86.3%</td>
<td>100%</td>
<td>98.2%</td>
<td>2,597</td>
</tr>
<tr>
<td>S. California</td>
<td>79.9%</td>
<td>100%</td>
<td>97.7%</td>
<td>1,213</td>
</tr>
<tr>
<td>Average</td>
<td>75.3%</td>
<td>99.6%</td>
<td>97.7%</td>
<td>17,636</td>
</tr>
</tbody>
</table>

perform in-motion WPT, we can see that in-motion WPT significantly increases the fraction of daily trip chains that can be met using the small range (25 mi, 40km) EV. Under the baseline in-motion WPT infrastructure rollout scenario, between 93% and 98.9% of the daily driving samples can be met by this short-range WPT-enabled EV. Note that if the proposed infrastructure deployment rates are not reached, a slightly higher range WPT-enabled EV may be necessary.

B. Vehicle, Infrastructure, Operations, and Maintenance Costs

Economic results are developed first on a vehicle level and then on a national level. Fig. 3 presents the national average vehicle purchase, operations, and maintenance costs on a per mile basis, and shows that summed costs for the WPT vehicles decrease by 44.8% for light duty vehicles and by 63.2% for Class 8 trucks, compared to conventional ICE vehicles. For each case, and each cost category (maintenance, purchase, and operations) the in-motion WPT EV is found to have cost savings relative to ICE vehicles. Note that operational costs are fueling/charging costs costs averaged across all computed geographic operation regions as described in Section II-B2.

Including the cost of the in-motion WPT infrastructure with vehicle-level cost savings allows for the modeling of national economic costs and the payback period. Payback is achieved by a reduction in cost from fuel delivery and availability. The baseline scenario assumes 13,788 roadway miles electrified per year, and a retrofitting cost of $2.5 million per lane per mile ($1.6 million per lane per km) ±$1 million per lane per mile ($0.6 million per lane per km) as shown in Fig. 4. For the baseline infrastructure rollout and costing scenario, the payback period is 32 years. Higher rates of infrastructure rollout increase the cost, but decrease the payback period. Higher infrastructure costs can delay the payback period relative to the baseline by up to 10 years. Note that the range of $2.5±$1 million per lane per mile encompasses numerous technical systems currently in development as described in Section II-B2.

C. Environmental Results

Results comparing the vehicle-level environmental impacts of both conventional ICE vehicles and WPT EVs is shown...
Fig. 4: National Cost/Revenue curves for varying roadway miles electrified each year with sensitivity between costs of $1.5 million per lane per mile ($0.9 million per lane per km) and $3.5 million per lane per mile ($2.2 million per lane per km).

in Fig. 5. All criteria pollutants, except for PM$_{2.5}$ and SO$_x$, decrease by moving to an electrified transportation system. Both PM$_{2.5}$ and SO$_x$ increase due to the PM and SO$_x$ emissions of electricity generation in the Midwestern region of the U.S. An average reduction of GHGs of 66.0% and 72.4% is experienced by moving from ICEs to WPT EVs for light duty vehicles and Class 8 trucks, respectively. However, large differences in environmental impact are seen depending on geographic location. These GHG savings range from 35.3% for light duty vehicle and 48.8% for Class 8 trucks in Hawaii, to 81.4% for light duty vehicles and 84.7% for Class 8 trucks in Connecticut. These results are consistent with other studies evaluating the environmental costs and benefits of electrified transportation [88].

Fig. 6 depicts the total amount of U.S. GHG emissions with respect to time from light duty vehicles and Class 8 trucks under the baseline technology adoption scenario. As WPT EVs replace ICE vehicles the overall emissions from the transportation sector decreases as do the emissions from the ICE vehicles to be consistent with current trends. By year 63 all ICE vehicles are replaced by WPT EVs. The total emissions savings over the 50-year life of the system (excluding the environmental costs of the infrastructure construction) is 29.3 trillion kg CO$_2$-eq. or a 30.6% CO$_2$-eq. reduction compared to a business as usual scenario (i.e. a scenario were current overall emissions trends continue) as shown in Fig. 6.
Fig. 6: Varying emissions from light duty vehicles and Class 8 trucks as the in-motion WPT technology is adopted.

IV. DISCUSSION

These results demonstrate that the baseline in-motion WPT infrastructure scenario can realize vehicle-level and national-level economic and environmental benefits, while satisfying the sample set of US drive cycles at similar levels of satisfaction as an advanced EV with 300 mi (483 km) range. The results are applicable to both the light-duty and Class 8 truck fleet.

The results also demonstrate a near-term means to be able to electrify long-distance trucking, a transportation sector particularly resistant to efficiency improvements, electrification, and fueling changes. As an example, many studies of transportation electrification have proposed that long-distance Class 8 trucking is impervious to the economic and environmental benefits of electrification [89, 90]. Long-term studies, seeking to understand the means to electrify freight transportation in the US, have converged on electrified rail transport as a means to reduce the environmental costs of freight transport [91]. Studies have estimated the cost of rail electrification infrastructure at between $4.8 million per track mile ($3.8 million per km) [92] and $55 million per track mile ($34 million per km) [93]. Economic comparison of in-motion WPT to electrified rail demonstrates that the in-motion WPT freight transportation system can realize the environmental benefits of freight electrification but at a significantly lower cost than electrified rail.

To understand these tradeoffs between the costs of in-motion WPT infrastructure and the benefits realized, we have investigated three additional infrastructure rollout scenarios which are shown in Fig. 7. Satisfaction for both drive cycle and vehicles using in-motion WPT was evaluated for four varying infrastructure deployment scenarios which are shown as red x’s on the plot. From left to right, these scenarios include: no in-motion WPT corresponding to 72% satisfaction, all primary roadways which corresponds to 87% satisfaction, all paved roadways (primary, secondary, and local) with speed limits greater than 60 mph (97 kph) which corresponds to 92% satisfaction, and a customized infrastructure (primary and secondary roadways) with speed limits greater than 30 mph (48 kph) which corresponds to 98% satisfaction. A exponential fit was applied to these three data points to estimate the cost for drive cycle and vehicle satisfaction with the technology. For all scenarios, a 25 mi (40 km) EV range, in-motion charging at 50 kW, and stationary charging at locations stopped greater than 1 hour was assumed for all vehicles. As an example, if 20,682 miles were electrified per year at a cost of $2.5 million per lane per mile, the payback period for 100% satisfaction would be approximately 44 years, for 98% satisfaction it would be approximately 28 years, for 92% satisfaction it would be approximately 12 years, and for 87% satisfaction it would be approximately 4.3 years.

The resulting curve for drive cycle satisfaction exponentially increases from the case when no in-motion charging takes place (72%) up to $2.26 trillion for 100% drive cycle satisfaction, shown in Fig. 7. In order to achieve the last 2.3%
of drive cycle satisfaction, an additional capital investment of $0.8 trillion is required corresponding to an infrastructure cost 1.5x more than the original investment that satisfies 98%. However, results show that this technology is expected to make a profit of $124 billion annually once all high-speed primary and secondary roadways are electrified representing a significant opportunity to electrify other roadways and improve technology adoption. Additionally, the sensitivity analysis showed that even if part of the infrastructure is built, there are still significant environmental benefits realized.

![Drive Cycle Data Point vs Drive Cycle Curve Fit](image)

Fig. 7: An infrastructure cost vs drive cycle satisfaction curve for real world drive cycles and vehicles.

V. Conclusions

This 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. The baseline WPT infrastructure proposal retrofits all high-speed (greater than 30 mph, 48 kph) primary and secondary roadways in US with in-motion WPT infrastructure. Coupled with more conventional stationary charging, this infrastructure enables a light-duty and Class 8 fleet of EVs with 25 mi (40 km) range to meet 97.7% of the sample set of n=17,636 24-hour longitudinal drive cycles. Time realized economic models show a national ROI of 32 years with $98 billion per year savings under conservative electricity and fueling cost projections. The environmental benefits of in-motion WPT-based electrification of the vehicle fleet are also sizable. The total emissions from light duty vehicles and Class 8 trucks will be reduced by 29.3 trillion kg CO₂-eq. (30.6% reduction) when compared to a business as usual scenario for the first 50 years of technology deployment. Overall, results show that in-motion charging using WPT can realize both economic and environmental benefits when compared to either conventional ICE transportation or a long-range EV fleet.

In-motion WPT is particularly important to long range trucking applications which have historically been difficult to demonstrate environmental and cost benefits from electrification. Additionally, in-motion WPT provides a significantly cheaper alternative to electrified rail transportation solutions which is the current state-of-the-art for long term sustainable freight transportation. 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, and it is easily deployable through current vehicles and road systems. Future work will focus on additional economic modeling details such as the impact of varying interest rates on system profitability as well as incorporating other near-future technologies such as autonomous vehicle operation and predictive energy management for improved environmental and economic benefits.

APPENDIX A

Additional Analysis Details

The ICE vehicle models (discussed in Section II-A) were developed using an overall force balance on the vehicle which provides the propulsive force required to propel the vehicle, \( F_{\text{prop}} \), defined as

\[
F_{\text{prop}} = m\dot{v} + C_r r m g + \frac{1}{2} C_d \rho \text{air} v^2 A_{\text{front}} + m g \sin \theta \tag{1}
\]

where \( C_r \) is the coefficient of rolling resistance, \( m \) is the mass of the vehicle, \( g \) is the acceleration due to gravity...
(9.81 \text{ m/sec}^2), C_d$ is the coefficient of drag, $\rho_{\text{air}}$ is the density of air (1.1985 kg/m$^3$), $v$ is the vehicle velocity, $A_{\text{front}}$ is the frontal area, $\dot{v}$ is the vehicle acceleration (calculated using a numerical derivative), and $\theta$ is the elevation angle. Starting from this overall equation, detailed models of various powertrains were developed in Matlab/Simulink.

Once verified, vehicle dimensions from the ICE models were used in the WPT EV models which also incorporate the necessary parts for in-motion WPT as shown in Fig. 8.

Fig. 8: Diagram of the in-motion WPT system implementation.

The range of WPT power charging that is installed on US roadways, the power of stationary charging infrastructure, and the EV range of the vehicles was varied (as discussed in Section II-B) and a summary table of these ranges is shown in Table III.

As discussed in Section II-B2, the cost of WPT installation was set at $2.5$ million per lane per mile based on the detailed calculations shown in Table IV. If the delivered power level increases, an increased form factor for the electronics would slightly increase the roadway cost but may significantly increase the electronics and grid connection which is why a sensitivity analysis of the $2.5$ million per lane per mile cost was conducted. The easiest way to increase the power to the vehicle is multiple receiver pads on the vehicle. Based on vehicle modeling, it is expected that the 50 kW is sufficient, however for larger vehicles, multiple pads could be required.

### Table III: Analysis of ranges of WPT power levels, stationary charging levels, and ranged vehicles.

<table>
<thead>
<tr>
<th>Battery Range</th>
<th>WPT</th>
<th>Supercapacitors</th>
<th>Satisfied</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0</td>
<td>0</td>
<td>79.8%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>7</td>
<td>91.0%</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>10</td>
<td>94.5%</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>13</td>
<td>96.0%</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>20</td>
<td>99.0%</td>
</tr>
<tr>
<td>25</td>
<td>100</td>
<td>50</td>
<td>98.6%</td>
</tr>
<tr>
<td>30</td>
<td>25</td>
<td>13</td>
<td>97.3%</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>0</td>
<td>83.7%</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
<td>17</td>
<td>99.3%</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
<td>13</td>
<td>99.9%</td>
</tr>
<tr>
<td>20</td>
<td>25</td>
<td>13</td>
<td>91.4%</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
<td>73.6%</td>
</tr>
<tr>
<td>35</td>
<td>0</td>
<td>0</td>
<td>87.1%</td>
</tr>
<tr>
<td>35</td>
<td>50</td>
<td>10</td>
<td>98.8%</td>
</tr>
<tr>
<td>35</td>
<td>25</td>
<td>13</td>
<td>97.7%</td>
</tr>
<tr>
<td>300</td>
<td>0</td>
<td>0</td>
<td>99.6%</td>
</tr>
</tbody>
</table>

### Table IV: A breakdown of the $2.5$ million per mile per lane cost equating to $960K$ electronics, $240K$ grid connection, and $1.2$ million roadway.

<table>
<thead>
<tr>
<th>Onsite Category</th>
<th>Time (Days)</th>
<th>Task Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic Control</td>
<td>1</td>
<td>Median (Barrier) Signs</td>
<td>$61,855</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cones</td>
<td>$1,553</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mill</td>
<td>$5,835</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Haul milled material Surface Grader</td>
<td>$63,318</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>PCC Material Cost Portable Batch Plant</td>
<td>$389,570</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pour/ Transport Concrete Paver</td>
<td>$11,651</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Surface Treatment Broom Finish</td>
<td>$488,717</td>
</tr>
<tr>
<td>Total</td>
<td>11</td>
<td>Total</td>
<td>$1,201,581</td>
</tr>
</tbody>
</table>

**ACKNOWLEDGMENT**

The authors acknowledge financial support from the Utah Science, Technology, and Research Initiative (USTAR), Utah
State University, Colorado State University, and the Governors Office of Energy Development in Utah. They also acknowledge research support from the Electric Vehicle and Roadway (EVR) group at Utah State University and additional support from Benjamin Vegel, Kelli Morrill, and Danna Quinn.

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