Electrification of Class 8 Trucking: Economic Analysis of In-Motion Wireless Power Transfer Compared to Long-Range Batteries

Evan Sproul, David A. Trinko, Zachary D. Asher, Braden Limb, Thomas H. Bradley, Jason C. Quinn
Colorado State University
Fort Collins, CO, USA
jason.quinn@colostate.edu
Regan Zane
Utah State University
Logan, UT, USA

Abstract—In-motion wireless power transfer (WPT) has been demonstrated as a safe and viable technology for operating and recharging electric vehicles while meeting consumer demands. In this research, in-motion WPT is applied to an electrified class 8 line-haul truck and evaluated for economic and environmental impacts. The results of this in-motion WPT truck architecture are compared against a conventional internal combustion engine (ICE) truck architecture and a long-range battery electric truck architecture. Results of this research show that in-motion WPT has the potential to reduce truck operational greenhouse gas emissions by 12% compared to ICE trucks and 7% compared to long-range battery trucks. This analysis supports the viability of in-motion WPT and identifies key areas for future assessment of vehicle architectures.

Keywords—wireless power transfer, electric vehicle, electric truck, vehicle modeling, techno-economic analysis, life-cycle assessment

I. INTRODUCTION

Fossil fuel combustion from internal combustion engine (ICE) vehicles has been shown to create health [1, 2], environmental [3, 4], and economic issues [5]. Adoption of hybrid electric vehicles [6] and fully electric vehicles [7] can significantly reduce these issues. Due to high battery costs and energy density issues these technologies have, to date, been limited to small passenger vehicles. Hybrid and fully electric trucks are still in development and are expected to be released by major automotive manufacturers in the near future [10–12]. The transition from a combustion based architecture to electric architecture represents a variety of challenges in terms of energy storage and delivery.

Currently, the majority of freight transportation is done through the use of class 8 line-haul trucks. In the U.S., these trucks compose just 2.5% of the total truck fleet but are responsible for 20.7% of fuel use due to the long distances traveled [8]. Additionally, due to their high fuel consumption and regular maintenance requirements, operational costs can be as high as 62 cents per mile [9]. Numerous automotive suppliers are working on solutions to these issues. Fuel cell hybrid electric and fully electric class 8 trucks are in development and planned for release between the years 2019 and 2021 [10–12]. Publically available images of these near future vehicles are shown in Figure 1. However, these technologies face range and refueling issues, a problem which can be alleviated through in-motion wireless power transfer (WPT) [13–20].

Fig. 1. Conceptual images of the Nikola fuel cell hybrid electric semi-truck (a) [10], the Toyota fuel cell hybrid electric semi-truck (b) [11], and the Tesla fully electric semi-truck (c) [12].

The feasibility of in-motion WPT charging applied to small transportation vehicles has been previously evaluated. Large-scale evaluations have implemented zero-order modeling to investigate the economics and environmental impact of the technology [19, 20] and used average energy consumption based on standard drive cycles [18, 21]. The fidelity of
modeling was improved through the use of real world drive cycle data with results showing a return on investment (ROI) of 11.3 years with a 25% fleet penetration but assuming all energy savings was dedicated to infrastructure payback [22]. WPT is a promising technology and as development has progressed, it is emerging as a safe, low cost, and superior recharging technique compared to physically plugging in a vehicle or when using overhead catenary cables [14, 16, 23–27]. An extension of existing WPT research is to apply it to in-motion vehicle charging which has been successfully demonstrated by various researchers [13, 28, 29]. This study expands upon previous work by evaluating the specifics of implementing in-motion WPT with electrified class 8 line-haul trucks. Results of in-motion WPT are compared to long-range fully electric and traditional ICE architectures. Discussion focuses on identifying areas in need of further research.

II. METHODS

The methods implemented for this research consisted of three primary steps. First, high-fidelity computational models of class 8 line-haul trucks were developed in the Autonomie modeling software for in-motion WPT, ICE, and long-range battery architectures. Second, real world drive cycles of class 8 line-haul trucks were acquired from a research database and integrated with vehicle models to simulate the performance of the different architectures. Lastly, the energy consumption recorded in drive cycle simulations was used to analyze the economic and environmental impact of the in-motion WPT, ICE, and long-range battery architectures. The following sections outline the specific details of each of these three primary steps.

A. Vehicle Model Development

High-fidelity class 8 line-haul truck models were created in the Autonomie modeling software developed by Argonne National Labs (ANL) [30]. Custom models were necessary to capture the fully electric class 8 truck architectures [12]. These models were created by modifying the parameters of preloaded architectures to be consistent with anticipated vehicle performance and available specifications [31-32]. Three models were used in the analysis: (1) an ICE architecture based on the Freightliner Cascadia, (2) a small battery electric architecture for use with in-motion WPT, and (3) a long-range battery electric architecture [12].

Specifications for fully electric trucks are not yet available, so as an estimate, the unloaded mass of the fully electric truck was assumed to be equal to the unloaded mass of the ICE truck (20,000 lbs). This allowed for a maximum modeled payload of 60,000 lbs in accordance with U.S. trucking regulations [33]. The unloaded mass for the WPT architecture (2) was determined to be equal to the unloaded mass of the long-range battery architecture (3), minus a difference in mass due to the smaller battery requirements. For a battery with a capacity reduction of 600 kWh and a specific energy of 150 Wh/kg, the weight reduction is 4,000 kg, or approximately 9,000 lbs [34]. For a fair comparison, all loaded trucks were modeled with an equivalent payload.

Note that the in-motion WPT concept includes WPT receiving pads and a supercapacitor bank to receive power pulses to then satisfy motor/generator and accessory load requirements first, with any excess used to charge the onboard battery at 2C levels to ensure battery integrity and life [35-37]. The additional weight of these system was included in the vehicle characterization. The overall efficiency for energy transfer from the grid to energy storage on-board the vehicle through WPT is 87% [38,39].

B. Drive Cycle Development

The real-world drive cycles used for analysis were from the National Renewable Energy Laboratory Fleet DNA project [40]. In total, 738 hours of drive cycles from 21 separate class 8 long-haul trucks were analyzed in Autonomie simulations of in-motion WPT, ICE, and long-range battery architectures. Modeled trucks were assumed to have sufficient energy storage capacity, stationary charging, or in-motion WPT charging to meet each full drive cycle. Performance of each vehicle was recorded in terms of fuel or electricity consumption over the duration of the drive cycles. This energy consumption was then used to develop economic and environmental impact assessments. An example of one of these real world drive cycles is shown in Figure 2.

![Fig. 2.](image-url)
smaller battery, supercapacitors, and WPT charging pads results in an overall savings of $60,000 per truck. Applying this savings resulted in an estimated in-motion WPT purchase price of $120,000. This lowered cost is the result of a small battery architecture that avoids the large costs associated with long-range batteries. All purchase prices were analyzed as a 10-year loan with 8% interest. Maintenance costs of the ICE and electric architectures were set at 4% and 2.5% of the purchase price per year, respectively [9,42]. It is common for automotive companies to warranty batteries for the life of the vehicle [43]. As a result, battery replacement costs were excluded from this analysis. Modeled vehicles were assumed to drive an average annual vehicle distance 65,897 miles per year [44] over a 15-year lifetime [45]. Trucks were modeled to operate at fully loaded capacity for 85% (56,012 miles) of each year, with the remaining 15% (9,885 miles) being driven while unloaded. Fuel and electricity costs were considered constant over the truck’s lifetime due to the lack of predictability in energy markets over the next 15 years [9].

Life-cycle assessment was performed to understand the operational greenhouse gas emissions associated with each vehicle architecture. The assessment was based on average energy (i.e. fuel or electricity) consumption over drive cycle simulations. Life-cycle inventory data including carbon dioxide emissions, methane emissions, and nitrous oxide emissions [46,47] were applied to energy consumption yielding the total greenhouse gas emissions of each vehicle. 100-year global warming potentials defined by the Intergovernmental Panel on Climate Change were then leveraged to translate all emissions to kgCO₂-eq [48]. The functional unit for this analysis was one mile of transport.

III. RESULTS

The high fidelity simulations of the in-motion WPT, ICE, and long-range battery class 8 trucks were used with drive cycles from NREL’s Fleet DNA project to determine energy consumption. This energy consumption was then integrated into economic and life-cycle modeling to evaluate the overall costs and operational greenhouse gas emissions for a single vehicle. Figure 3 shows a significant reduction in overall cost for utilizing in-motion WPT in class 8 trucks.

As expected, electrifying trucks dramatically decreases operational costs. Furthermore, the low purchase price of in-motion WPT generates significant savings compared to long-range battery trucks. These savings are a direct result of avoiding the high costs associated with long-range batteries. Maintenance costs between the long-range battery and in-motion WPT trucks are found to be slightly different. This difference is primarily due to the correlation between purchase price and maintenance costs within economic models.

This analysis assumes infrastructure would be deployed on all high speed roadways thus meeting the needs of class 8 trucks. The ownership of the in-road charging infrastructure has not been fully defined based on the current state of the technology. As a result, the economic results presented do not include an expected infrastructure usage fee. However, the results from this work show even with an $0.14 per mile usage fee, in-motion WPT could still be competitive with long-range battery trucks. Furthermore, doubling this usage fee to $0.29 per mile, the in-motion WPT costs would be competitive with those of ICE. Based on current estimates, the capital investment required for the deployment of the infrastructure across the interstate system in the US would be $235 billion. While this represents a significant investment, a $0.10 per mile usage charge would generate approximately $50 billion per year corresponding to a 5-6 year payoff back time. This payback time does not include infrastructure role out or adoption which would extend the timeframe. Another item that is not accounted for in this research is degradation of long-range batteries, which could be costly and further increase the maintenance costs of long-range battery trucks. Including this in further analysis could demonstrate an even larger advantage for the smaller batteries of in-motion WPT trucks.

Energy usage results were combined with life-cycle inventory data to evaluate the greenhouse gas emissions from operating the three different truck architectures. Figure 4 shows a reduction in greenhouse gas emissions in both electric architectures when compared to ICE. Long-range battery vehicles show a 5% reduction for both loaded and unloaded trucks. In-motion WPT shows a 16% reduction when unloaded and a 11% reduction when loaded. The decrease in emissions is a direct result of reduced energy consumption in the electric architectures. This decrease is enough to counteract the fact that electric vehicles are often powered by coal based electricity systems that can actually drive higher greenhouse gas emissions. Integrating in-motion WPT with low emission electricity generation technologies such as wind or solar power would further reduce the operational greenhouse gas emissions. The results of this study are based on a grid electricity mix of 34% coal, 32% natural gas, 20% nuclear, and 13% renewable [43].
Fig. 4. Comparison of operational greenhouse gas emissions of internal combustion engine, long-range battery, and in-motion wireless power transfer truck configurations.

IV. CONCLUSIONS AND FUTURE WORK

In this study, three high-fidelity class 8 truck models were developed in the Autonomie modeling software: an ICE powered truck, an in-motion WPT truck, and a long-range battery truck. Each of these trucks were then simulated over numerous real-world drive cycles from the NREL Fleet DNA project in both the unloaded and fully loaded conditions. An economic analysis including upfront purchase and operational costs was then performed based on the simulation results. As expected, the electrified vehicles offer significant cost saving and greenhouse gas emission reductions, with the in-motion WPT solution proving to be better than the long-range battery trucking solution. When compared to ICE and long-range battery trucks, in-motion WPT shows the potential to reduce operational greenhouse gas emissions while proving to be an economically favorable system. The single largest advantage of in-motion WPT is the use of small batteries that avoid large costs associated with long-range electric batteries upfront. Otherwise, the operational characteristics of in-motion WPT are similar to that of long-range battery trucks. This preliminary analysis sheds light on an interesting and perhaps undervalued solution to transportation sustainability and can be used to assess and guide decision making as new transportation technologies are explored.

Building upon this analysis, there are several opportunities for future work. First, current analysis can be improved by accounting for elevation changes within drive cycles. Elevation will have an impact on overall energy consumption and could impact the viability of in-motion WPT. Second, the implementation of WPT allows for unique controls schemes that can optimize energy consumption such as driver-less control or Eco-Driving [49]. Exploring the impacts of these schemes will be a vital step in expanding the potential of in-motion WPT technology. Lastly, incorporation of infrastructure costs and fleet-level benefits into the economic models will be key in understanding the full cost of in-motion WPT technology. Previous work involving passenger cars and nationwide infrastructure can be leveraged to gain a complete understanding of the feasibility of deploying in-motion WPT in class 8 long-haul trucks.

ACKNOWLEDGMENT

The authors acknowledge funding support from the Department of Energy (Grant DE-AR0000885).

REFERENCES


[48] Intergovernmental Panel on Climate Change, Climate change 2013 the physical science basis, Cambridge University Press, New York, NY, 2013.