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Project Title:
Optimal Deployment of Dynamic Charging Lanes for Plug-in Hybrid Trucks

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Research Needs:
In the United States, the transportation sector accounts for 71% of total petroleum consumption and 27% of total greenhouse gas (GHG) emissions (USDOT, 2017). Due to increased travel demands and limited improvements in fuel efficiency, petroleum consumption in the transportation sector has increased by 27% since 1990 (USEIA, 2017). Within the transportation sector, road freight transportation is by far the second largest consumer, as it accounts for about 20% of all transportation petroleum consumption. Furthermore, conventional freight trucks are primarily powered by diesel, which is a primary source of particulate matter (PM) and nitrogen oxides (NOx) emitted by motor vehicles. Plug-in hybrid electric truck (PHET) technology, which has improved fuel economy and reduced emissions, offers a great alternative powertrain for freight transportation.

Compared to conventional diesel trucks, the advantages of PHETs are twofold. First, the electric energy in on-board battery packs can substitute for a significant portion of petroleum consumption. Second, the combination of an internal combustion engine (ICE) and an electric propulsion system can improve energy efficiency through optimization of the engine's operation and recovery of kinetic energy during braking. Furthermore, PHETs avoid the disadvantage of limited driving range for battery electric vehicles (BEVs) and eliminate the "range anxiety" of drivers. Due to the limitations of battery technology, long-distance road freight transportation using only electric-powered mode is not currently cost-competitive, and hence not practical.

Dynamic charging technology, also referred to as charging-while-driving (CWD), offers the promise of further reducing diesel consumption of PHETs and promoting the electrification of road freight transportation. Dynamic charging can convert road segments into charging lanes through the installation of conductive or inductive charging facilities, thus providing PHET drivers with the ability to charge PHETs while in motion. The technology can further reduce petroleum consumption of PHETs by supplying additional electric energy en route. Conductive charging based CWD has been used in electric trains and trams for more than a century. Siemens adapted this technology for use in trucks and developed a so-called eHighway system that can electrify road freight transportation (Grünjes and Birkner, 2012). Inductive charging applied to electric vehicles has been proposed by the California Partners for Advanced Transit and Highways (PATH) as early as the 1990s (PATH, 1996). Since then, numerous studies have been undertaken to improve and verify the applicability of inductive charging based CWD (e.g., Covic et al., 2000; Boys et al., 2002; Huang et al., 2009; Huh et al., 2011; Choi et al., 2013; Cirimele et al., 2014; Chen et al., 2015; Fuller, 2016). The Korea Advanced Institute of Science and Technology (KAIST) in South Korea has developed an online electric vehicle (OLEV) system using dynamic wireless charging technology and has implemented it in the shuttle system of the KAIST campus (Suh et al., 2011). Utah State University (USU) has constructed an electrified test track and has demonstrated that in-motion electric vehicles can be effectively and safely charged through dynamic wireless charging (Morris, 2015; Liu and Song, 2017). As argued in Chen et al. (2017), commercial fleets, such as buses and trucks, are likely to be early adopters of dynamic charging infrastructure due to higher benefits offered to these vehicles. Commercialization of CWD technology for commercial vehicles is on the horizon. The OLEV system has been applied in the trolley system of Seoul Grand Park and on a bus line in Gumi City (Jang et al., 2015). Scania and Siemens have built a two-kilometer electric road on the E16 motorway in Sweden (Scania, 2016). Siemens has signed a contract with the South Coast Air Quality Management District (SCAQMD) in California to install and demonstrate its eHighway system in the proximity of the ports of Los Angeles and Long Beach (Siemens, 2015). As a result, this study will focus on the deployment of dynamic charging infrastructure for PHETs in a road freight transportation network.

To effectively implement CWD technology in trucking freight transportation, charging lanes need to be strategically deployed in the road network connecting logistics centers, such as ports, terminals, and distribution centers. The charging lane deployment problem is twofold. First, it is necessary to determine the optimal location for the construction of charging lanes. Second, one must consider the influence of deployed charging lanes on the route choice behaviors of drivers, especially drivers of PHETs. The behaviors of drivers in a transportation network are usually described with a user equilibrium (UE) assignment model. Although a number of studies have formulated UE models considering electric vehicles (e.g., Jiang et al., 2012, 2014; He et al., 2014, 2015, 2016; Chen et al., 2016), none of them are capable of describing the behaviors of PHET drivers in a network with charging lanes. An electric motor has much higher energy efficiency than an ICE, and as a result, PHET drivers can significantly reduce fuel costs by consuming electricity instead of petroleum fuel (Granovskii et al., 2006; Nanaki and Koroneos, 2013; USDOE, 2017). Therefore, PHET drivers may simultaneously consider travel time and fuel costs when traveling from their origin to their destination and may prefer routes with charging lanes. These two problems should be treated simultaneously in a network setting.

Research Objectives:

1. Develop an optimization framework that determines the construction location of dynamic charging lanes in a road freight transportation network and explicitly considers the influence of deployed charging lanes on the route choice behaviors of drivers simultaneously.
2. Conduct a case study to demonstrate the viability and the benefit of applying dynamic charging technology to an electrified road freight transportation system with PHETs.

This project is to propose a modeling framework to deploy dynamic charging lanes for PHETs in an electrified road freight transportation system. The proposed project will accomplish the above objectives.

Research Methods:

In the proposed research, we will formulate a dynamic charging lane deployment problem in a bi-level mathematical programming framework. The objective of the optimization problem is to find the optimal location for deploying dynamic charging lanes to optimize system performance of the network (e.g., total system travel costs, total system petroleum consumption, total system emissions, or a combination thereof) subject to the budget constraints and equilibrium behaviors of drivers.

System performance associated with a charging lane deployment plan is assessed based on the equilibrium route choice behaviors of drivers in response to the plan. Two classes of vehicles will be considered in the network, i.e., conventional ICE passenger cars and PHETs. Passenger car equivalence (PCE) will be used to evaluate the impact of PHETs on traffic flows. PHET drivers, when traveling from their origin to their destination, strive to minimize total travel costs, which includes travel time and fuel costs. They can choose their routes, determine whether to use electric energy, and decide whether and for how long to charge on charging lanes. Before the state of charge (SOC) for an on-board battery in a PHET reaches its lower limit, the driver can always choose to use electricity instead of diesel to reduce fuel costs. Moreover, when traveling on a charging lane, the potential charging time of a PHET is determined by its speed, thus driving speed is also a critical decision for drivers. Conventional ICE passenger car drivers may only consider travel time when choosing routes because fuel costs and travel time on a route usually display similar trends (Daganzo and Sheffi, 1977). A multi-class, multi-criteria UE model will be proposed to describe drivers' route choice behaviors and the resultant network flow distribution. Based on the UE model, an optimization problem will be formulated to determine the construction location of charging lanes. Proper solution algorithms will also be explored depending on the properties of the formulated models.

Numerical studies will be conducted to demonstrate the proposed methodology. The results will also be used to illustrate the potential of employing dynamic charging technology in an electrified road freight transportation system.

Expected Outcomes:

The project is expected to produce an optimization framework to deploy dynamic charging lanes for PHETs in an electrified road freight transportation system. The research findings will not only have theoretical significance, but will also offer a wide range of applications in implementing more sustainable road freight transportation systems. The end product will be useful to transportation agencies in developing sustainable road freight transport systems.

Relevance to Strategic Goals:

- Economic Competitiveness
- Environmental Sustainability

The proposed project contributes to three goals of Mountain-Plains Consortium, i.e., environmental sustainability, livable communities, and economic competitiveness. Road freight transportation currently relies on heavy-duty diesel trucks, which consume vast amounts of petroleum and emit pollutants. The proposed dynamic charging lanes and PHETs can significantly reduce petroleum consumption and local emissions, which will improve the environmental sustainability of road freight transportation and the livability of communities around logistics centers. Furthermore, an electrified road freight transportation system can reduce freight transportation costs, which will in turn support the economic competitiveness of a region.

Educational Benefits:
One graduate student will be involved in the research and receive training in transportation network modeling, optimization, and road freight transportation. The research results will provide fresh materials and case studies to expand the transportation curricula at USU.

Tech Transfer:
Research results will be disseminated through publication in peer-reviewed professional journals and presentations at state and national meetings and conferences. All data collected from the research project will be stored in a repository such that the information will be easily retrievable should anyone wish to use it. Research results will also be incorporated into a wide variety of education, training, outreach and workforce development activities.

Work Plan:

1. Literature Review
2. Formulating the Optimal Deployment Problem
3. Solving the Optimal Deployment Problem
4. Case Study
5. Report Writing

Literature Review (2 months): We will conduct a thorough literature review on dynamic charging technology and its applications in the transportation industry.

Formulating the Optimal Deployment Problem (5 months): We will formulate the optimal deployment of charging lanes for a freight transport network as a mathematical programming problem.

Solving the Optimal Deployment Problem (4 months): We plan to explore and compare solution algorithms identified in the literature review.

Case Study (5 months): We will conduct several numerical studies to demonstrate the proposed methodology. Sensitivity analysis will be conducted to assess the impact of on-board battery size and the relative price of electricity and diesel in the deployment of charging lanes.

Report Writing (2 months)

Project Cost:

Total Project Costs:	$119,468
MPC Funds Requested:	$59,734
Matching Funds:	$59,734
Source of Matching Funds:	Faculty Salary

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