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Dynamic charging infrastructure deployment for plug-in hybrid electric trucks

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ABSTRACT

Inspired by the rapid development of charging-while-driving (CWD) technology, plans are ongoing in government agencies worldwide for the development of electrified road freight transportation systems through the deployment of dynamic charging lanes. This en route method for the charging of plug-in hybrid electric trucks is expected to supplement the more conventional charging technique, thus enabling significant reduction in fossil fuel consumption and pollutant emission from road freight transportation. In this study, we investigated the optimal deployment of dynamic charging lanes for plug-in hybrid electric trucks. First, we developed a multi-class multi-criteria user equilibrium model of the route choice behaviors of truck and passenger car drivers and the resultant equilibrium flow distributions. Considering that the developed user equilibrium model may have non-unique flow distributions, a robust deployment of dynamic charging lanes that optimizes the system performance under the worst-case flow distributions was targeted. The problem was formulated as a generalized semi-infinite min-max program, and a heuristic algorithm for solving it was proposed. This paper includes numerical examples that were used to demonstrate the application of the developed models and solution algorithms.

1. Introduction

Trucks are an important part of modern freight transportation. According to the American Trucking Association (ATA) (2016a), trucks were used for the transportation of 70.1% of the domestic freight tonnage in the United States in 2015, accounting for 81.5% of the nation's total freight bill. With the growth of the national economy, particularly in manufacturing, consumer spending, and international trade, it is forecasted that the truck tonnage will increase by 27% between 2016 and 2027 (ATA, 2016b). However, current trucks are mainly powered by fossil fuel, which have a low energy efficiency and high level of exhaust emission. A recent study by the American Transportation Research Institute (ATRI) found that more than 99.5% of trucks in the United States in 2016 utilized fossil fuel (Torrey and Murray, 2016). Moreover, most medium and heavy trucks use diesel fuel, which accounts for 89.6% of the energy consumption by medium and heavy trucks in the United States in 2014 (Davis et al., 2016). Diesel engines are a primary source of particulate matter (PM) and nitrogen oxides (NOx) emissions, and the development of a more sustainable road freight transportation system requires the urgent replacement of diesel-engine trucks with more energy-efficient and low-emission trucks.

Among the available alternative powertrains for trucks, plug-in hybrid electric truck (PHET) technology is widely considered to be promising for achieving significant increase in fuel economy and decrease in emission (e.g., Burton et al., 2013; CalETC, 2015; Johannesson et al., 2015; Okui, 2016). Compared to conventional internal combustion engine (ICE) trucks, the advantages of PHETs are twofold. First, when fully charged, the on-board battery pack of a PHET is capable of substituting a significant amount of fossil

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fuel consumption. Second, the combination of an ICE and electric motor improves the energy efficiency through the optimization of the engine operation and recovery of kinetic energy during braking. Furthermore, battery electric truck (BET) technologies are not currently mature enough for long-haul operations. Sripad and Viswanathan (2017) estimated that the battery pack of a 600-mile BET would weigh over 18 tons while its available payload is capped at 12 tons, implying that a BET would consume a greater fraction of energy in moving its battery pack rather than its payload. On the other hand, a PHET avoids the disadvantages of the limited driving range and long charging time of BETs. As reported in CalETC (2015), freight operators typically use a given truck for multiple routes of varying distances, and a PHET affords flexibility in daily operation, enabling greater utilization.

Although PHETs enable significant reduction of fossil fuel consumption relative to their diesel- and gasoline-engine counterparts, owing to battery technology limitations, long-distance road freight transportation using the electric-only mode is currently uneconomical and impractical. However, recent breakthroughs in charging technologies promise to enhance the utilization of PHETs. Among these innovative technologies, charging-while-driving (CWD) (Deflorio and Castello, 2017; Chen et al., 2018) has great potential for the future. Segments of existing roads can be converted into dynamic charging lanes through the installation of conductive or inductive charging facilities. PHETs equipped with the appropriate power receivers can then charge their batteries while traveling on such roads. This would enable further reduction of fossil fuel consumption by PHETs. In addition, PHETs enable drivers to operate them as conventional trucks outside dynamic charging lanes. In the light of the forgoing, the present study focused on the deployment of dynamic charging infrastructure for PHETs used for long-haul road freight transportation.

Conductive-charging-based CWD has been applied in electric trains and trams for more than a century. Siemens adapted the technology for trucks and developed the so-called eHighway system that can electrify road freight transportation (Grünjes and Birkner, 2012). The application of inductive charging to electric vehicles was also proposed as early as 1990s by California's Partner for Advanced Transit and Highways (PATH) (PATH, 1996). Since then, numerous studies have been conducted to improve and verify the feasibility of the innovation (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 developed an online electric vehicle (OLEV) system that utilizes dynamic wireless charging technology, and implemented it in the KAIST campus shuttle system (Suh et al., 2011). Utah State University constructed an electrified test track and demonstrated that in-motion electric vehicles could be effectively and safely charged through dynamic wireless charging (Morris, 2015; Limb et al., 2016; Liu and Song, 2017; Liu et al., 2017). As argued by Chen et al. (2017), commercial fleets, such as bus and truck fleets, are likely to be the early users of dynamic charging infrastructure because of the higher benefits that they stand to gain. The commercialization of CWD technology is indeed on the horizon. The OLEV system has already been applied to the trolley system at the Seoul Grand Park and a bus line in Gumi City (Jang et al., 2015). Scania and Siemens have also built a two-kilometer electric road on the E16 motorway in Sweden (Scania, 2016). Further, Siemens has worked with the South Coast Air Quality Management District (SCAQMD) in California to install and demonstrate the eHighway system in the proximity of the ports of Los Angeles and Long Beach (Siemens, 2015).

The effective utilization of CWD technology for road freight transportation requires the strategic deployment of the charging lanes in parts of the road network connecting logistics centers, such as ports, terminals, and distribution centers. This paper proposes a network modeling framework for improving the system performance by optimizing the locations of the charging lanes under limited budget.

To determine the optimal strategy for deploying charging lanes in a transportation network, a user equilibrium (UE) model should first be developed to describe the effect of a new design plan on the route choice behaviors of drivers, and the resulting traffic flow distributions. This study considered mixed traffic of passenger cars and trucks. We further envision that, to develop a sustainable road freight transportation system, the government and freight companies would work together to convert freight trucks using the network into PHETs, and deploy charging lanes for the trucks. The route choice behaviors of PHET drivers in a network with charging lanes should be explicitly considered in the UE model. There have been a few previous studies on the formulation of a network equilibrium model for electric vehicles. Considering the limited travel range of battery electric vehicles (BEVs), Jiang et al. (2012) introduced a path constraint for restricting the length of the paths usable by electric vehicles into a conventional UE model. Jiang et al. (2014) and Jiang and Xie (2014) investigated the network equilibrium problems involving mixed gasoline and electric vehicle flows. He et al. (2014, 2015, 2016), Xie and Jiang (2016) and Zheng et al. (2017) further developed a series of UE models in which the range of BEVs could be extended by charging at public charging stations. Wang et al. (2016) incorporated trip chain analysis into the UE problem involving BEVs. Xie et al. (2017) further extended this study by considering stochastic range anxiety of BEV users. Considering battery swapping and road grade, Xu et al. (2017) investigated network UE problems with mixed BEVs and gasoline vehicles. Nevertheless, charging lanes have not been considered in these studies. Chen et al. (2016) considered a futuristic road network with charging lanes and used by only BEVs, and built a novel user equilibrium model using modified equilibrium conditions. In their study, BEVs have limited battery capacity and may need to be recharged on charging lanes to ensure they have enough energy to reach their destinations. BEV users are assumed to select routes to minimize their travel time cost while ensuring not to run out of charge before reaching their destinations. In contrast, PHET drivers considered in our study do not have range anxiety and can have quite different route choice behaviors compared to BEV drivers.

The route choice behaviors of PHET drivers could be influenced by charging lanes. In conventional UE traffic assignment studies (e.g. Sheffi, 1985), travel time is often used as the sole criterion for route choices for travelers. Fuel cost can be neglected because it is highly correlated with travel time and thus exhibits the same trend with travel time. However, for PHETs in a transportation network with charging lanes, fuel cost and travel time could have quite different trends. Due to the fact that electric motors are much more efficient than ICEs, using electricity as vehicle fuel can reduce fuel cost by approximately 50% compared to using fossil fuel (Alternative Fuels Data Center, 2017). Therefore, for PHETs, a route with high travel time could have low fuel cost if charging lanes are deployed along the route to electrify the driving mode of these PHETs. Because PHET drivers can significantly reduce their fuel