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Project Title

Equitable Deployment of Wireless Charging Lanes in Transportation Networks

University

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Research Needs

As one of the most significant contributors to greenhouse gas (GHG) emissions, the transportation sector is responsible for 28% of greenhouse gas emissions in the United States (US EPA, 2015). Among the total share of emissions from the transportation sector, 60% is comprised of the emissions coming from light-duty vehicles, i.e., passenger cars and light trucks (US EPA, 2017). To alleviate GHG emissions, electric vehicles (EVs) are introduced as a promising solution to reduce tailpipe emissions, providing a more sustainable transportation system. Studies have shown that the CO2 emission per mile from an EV can reach less than half of the CO2 emission per mile from a conventional vehicle (Alternative Fuels Data Center, 2020). Another benefit of EVs is that their travel costs are approximately only 25% of conventional vehicles' travel costs (Kuby and Lim, 2007; Shukla et al., 2011; Capar and Kuby, 2012). The adoption of EVs has been boosted in recent years, which is primarily attributable to two reasons: 1) people's awareness of EVs' benefits to the environment and the well-being of society, and 2) government policies promoting EVs. As a result, in 2018 in the United States, the sales of plugged-in electric vehicles (PHEVs) reached nearly 140,000, experiencing a 79% increase when compared to 2017 (Irle, 2018). Although the EV market share currently seems marginal, it is predicted that this market share could reach 50% in 2030 (Chen et al., 2016). There are, however, certain unfavorable factors that may negatively impact EV market share. One primary factor is the limited driving range of EVs, ranging between 40 and 250 miles (Chung and Kwon, 2015; Loveday, 2020). This limited range leads to EV drivers' fear (or mental distress) of running out of electrical power in the middle of the road, known as "range anxiety" (Mock et al., 2010; Franke and Krems, 2013). Range anxiety can be alleviated by the deployment of public charging infrastructure, which subsequently promotes EVs (He et al., 2013; Nie and Ghamami, 2013; Chen et al., 2016).

Broadly speaking, public charging infrastructure can be categorized into stationary charging facilities (e.g., charging stations) and dynamic charging facilities (e.g., wireless charging lanes). To elaborate, a wireless charging lane is an electrified road segment, which facilitates dynamic power transfer to EVs that have the proper means to receive electrical power (Tavakoli and Pantic, 2017). Both charging stations and wireless charging lanes are essential components of future electrified transportation systems. However, charging lanes provide users with two extra benefits when compared with charging stations. First, EV drivers who have access to charging lanes are not required to detour to reach charging stations and wait for their cars to be charged, which can increase their travel time (cost). Second, charging lanes offer ubiquitous charging opportunities, which provide a sense of security to EV drivers. Subsequently, many researchers have investigated the practicality of charging lanes throughout the literature (Yu et al., 2011; Lukic and Pantic, 2013; Ning et al., 2013; Shinohara et al., 2013; Cirimele et al., 2014; Vilathgamuwa and Sampath, 2015; Vallecchi et al., 2017; Khan et al., 2019). Meanwhile, several institutes around the world constructed charging lanes in different locations to demonstrate their feasibility and practicality (Brecher and Arthur, 2014; Morris, 2015; Rim and Mi, 2017; Jang, 2018; SELECT, 2019; Azad et al., 2019). The above-mentioned studies demonstrated that wireless charging lanes are one of the most convenient and promising charging solutions that can eliminate range anxiety if they become prevalent in a regional transportation network.

To address the availability issue of charging infrastructure, ideally, the private and public sectors should work together. However, due to the currently limited market share of EVs, the private sector is lagging behind in building adequate charging facilities (Melaina, 2003; Stevens et al., 2008), and government support for the deployment of public charging infrastructure becomes crucial to end the charging infrastructure dilemma. Given the limited government budgets, the deployment of public charging infrastructure should address both efficiency and equity concerns.

From an efficiency perspective, several studies have investigated the deployment of charging infrastructure to maximize the utilization of charging lanes and minimize social costs. He et al. (2013) proposed a modeling framework to optimally deploy public charging stations. They used bi-level programming to model user behavior and incorporate an optimal pricing scheme based on locational marginal pricing, and, in the upper level, to optimally place the charging stations to maximize social welfare. Chen et al. (2016) presented a comprehensive framework that addressed the deployment problem of wireless charging lanes for EVs. Their framework explicitly captured EV drivers' speed choice behaviors when facing charging lanes. After combining the speed choice model and user equilibrium (UE), they added another optimization layer to optimally select the charging links. Liu and Song (2018) investigated the deployment of wireless charging lanes for electric trucks to enhance freight transportation and reduce heavy-duty truck emissions. They used different utility functions in their framework to address the multi-class traffic assignment problem. A min-max framework was then employed to better investigate the performance of a system in a situation in which solutions are non-unique.

Apart from the efficiency perspective, equity is another aspect that requires close investigation, especially for public charging infrastructure. As previously mentioned, to obtain an efficient deployment of charging lanes, researchers proposed approaches with the primary objective of maximizing social welfare or, equivalently, minimizing generalized total system costs (Chen et al., 2016; Liu and Song, 2018). However, a potential downside of minimizing total costs is the uneven impacts of deployment plans on users of different origin-destination (O-D) pairs. For example, certain groups of users may experience shortened travel time, while others may suffer from lengthened travel time due to a deployment plan. The equity impacts of deployment plans may greatly influence their public acceptance. Therefore, equity concerns in the deployment of public charging infrastructure must be addressed to gain critical public support.

The wireless charging lane deployment problem can be viewed as a generalized transportation network design problem (NDP). A limited number of studies have investigated the equity issue in transportation network design. Meng and Yang (2002) proposed a framework to investigate the benefit distribution among network users in terms of equilibrium travel cost changes in continuous NDPs. They proposed a multi-objective model to minimize: 1) the total travel time, and 2) a ratio of the equilibrium travel time of an O-D pair before changes in road capacity over the equilibrium travel time after the changes. They applied simulated annealing to solve their bi-level non-convex network design model. Caggiani et al. (2017) proposed a modeling framework to incorporate equity into NDP. They used a multi-objective fuzzy programming model to maximize user satisfaction while considering both horizontal and vertical equity criteria. Horizontal equity concerns the distribution of benefits between individuals and classes regarded as equal in terms of ability and need (Caggiani et al., 2017). Based on this definition, no individual or group should be favored over another concerning benefits and costs. Vertical equity indicates that different social classes with different income levels should be treated fairly, which means that no exclusions in designs are acceptable. Do Chung et al. (2018) introduced a modeling framework to incorporate equity into electric charging stations' allocations. In their modeling framework, they used two different types of equity: demand equity and flow equity.

To efficiently and equitably deploy charging lanes, one must consider the charging and route choice behaviors of EV drivers who follow a selfish decision-making procedure, as well as proper deployment strategies that guarantee the fair distribution of all benefits (e.g., accessibility and travel cost reduction) of charging lanes. However, a careful review of previous studies illustrated that researchers throughout the literature had not investigated the issue of fairness in terms of the distribution and the benefits of wireless charging lanes.

In this study, we envision that EVs are about to become common in the road network, and that governmental agencies are striving to apply an equitable and efficient deployment strategy to introduce wireless charging lanes into transportation systems. To the best of our knowledge, this study is the first in the literature to develop a modeling framework for the equitable and efficient deployment of wireless charging lanes in general transportation networks.

Research Objectives

This project proposes a modeling framework for the equitable and efficient deployment of wireless charging lanes. The proposed project will accomplish the following three objectives:

1. Develop a new charging time decision problem based on a modified utility function to encompass range anxiety's disutility.
2. Introduce a new network equilibrium model to describe the route choice behaviors of EV drivers in a transportation network.
3. Investigate various equity measurements and incorporate them into wireless charging lane deployment in a transportation network.

Research Methods

A bi-level programming framework is proposed to address the equitable and efficient deployment of wireless charging lanes in a transportation network. In the lower level of the bi-level problem, EV drivers who travel between their O-D pairs can select their paths and their battery charging plans to avoid running out of battery power, and to minimize range anxiety. A battery charging plan determines the amount of energy an EV should receive from charging lanes along a selected path (Chen et al., 2016). Additionally, EV drivers try to minimize their travel costs (Chen et al., 2016). The necessity of feeling secure and having enough energy might force individuals to choose routes containing charging lanes. In the upper level of the bi-level problem, the governmental agency (the system operator) strives to solve an equitable and efficient charging lane deployment problem. In this problem, the agency tries to select links for electrification so that the total system travel cost is minimized and the benefits of charging lanes are equitably distributed.

More specifically, EV drivers strive to minimize the charging costs at node, the path travel cost, and range anxiety's disutility in the charging time decision problem. The path travel cost also consists of two components: the path travel time, and the costs of charging on charging lanes along the path. Thus, under a given traffic flow distribution, EV drivers decide when and where to receive a necessary charge to minimize their travel costs (maximize their utility). Several decision variables exist in this problem: the state of charge at each node, the amount of energy received at the origin, the actual travel time on charging lanes, and the charging time.

The new network equilibrium model is expected to be modeled as non-linear complementarity constraints to describe EVs' route choice behaviors in a transportation network with charging lanes. The model considers two unique characteristics of EVs: 1) the tradeoff between static charging at origin and dynamic charging along the way, and 2) the tradeoff between the disutility of range anxiety and the cost of charging. For EV drivers, guaranteeing their arrival and lowering their costs are the primary concerns when making their charging plan and route choices. Thus, charging plans are introduced to the UE problem by integrating UE with the charging time problem's first-order optimality conditions. Finally, based on the newly proposed UE, a variational inequality (VI) model is formulated to facilitate the solution algorithm development. The new network equilibrium model can be used to evaluate the equity and efficiency of deploying wireless charging by transportation agencies.

Based on the proposed VI, we advance a general mathematical model to facilitate government agencies in equitably and efficiently deploying wireless charging lanes. The proposed model is structured as a Stackelberg leader-follower game, in which the government is the leader, and EV drivers are the followers. The leader determines the deployment of wireless charging lanes to maximize social welfare and ensure the fair distribution of benefits. The fair distribution of benefits is assured through different equity measurements (e.g., flow and demand equity). This decision-making process constructs our upper-level programming model. Given wireless charging lanes' deployment, EV drivers choose their charging plans and routes to complete their trips. The leader-follower game is formulated as a multi-objective mathematical program with complementarity constraints. It is transformed into a single-objective problem and is then solved by an efficient algorithm.

Numerical studies are proposed to evaluate the performance of the proposed framework, and sensitivity analyses are performed to identify the impacts of different factors on the equity and efficiency of a deployment plan in a transportation network.

Expected Outcomes

This project is expected to produce an advanced modeling framework for the equitable and efficient deployment of wireless charging lanes. The research findings carry theoretical significance, as well as policy implications, for government investments in road electrification. This study provides a fair and efficient solution to promote EVs, and to serve different user groups in a transportation network. The results may facilitate government decisions regarding the allocation of funds to equitably deploying charging lanes, thus increasing people's acceptance in transforming the transportation network into an emission-free system. The end product will help governmental transportation agencies to evaluate the impact of their future plans on network users' travel behaviors and social welfare.

Relevance to Strategic Goals

The proposed project contributes to the Mountain–Plains Consortium's two strategic goals: 1) economic competitiveness, and 2) livable communities. The first primary goal addressed by this proposed project is economic competitiveness. Through the efficient deployment of wireless charging lanes, governments can introduce EVs as means of sustainability, since EVs potentially incorporate renewable energy into the sources of energy used in the transportation sector. Deploying wireless charging lanes offers tremendous potential in promoting the adoption of EVs. As a result, the proposed modeling framework can help government agencies maintain a clean society while benefiting from low-cost renewable energy sources. Furthermore, the proposed project can render communities more livable by improving air quality and helping to ensure the environment is clean and emission-free.

Educational Benefits

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

Technology Transfer

Research results will be disseminated through 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

The proposed research will be conducted over 12 months according to the following schedule:

- Task 1: A literature review (1 month). We will conduct a thorough literature review on transportation modeling work related to wireless charging lanes and equity in public facility deployment.

- Task 2: Formulation of a new network equilibrium model (2 months). We will formulate a new network equilibrium model that describes charging plans and route choice behaviors in a transportation network utilized by EVs.
- Task 3: Formulation of an equitable and efficient deployment problem (3 months). We will propose a general mathematical model that helps government agencies to equitably and efficiently deploy wireless charging lanes.
- Task 4: Solution algorithm development (2 months). We plan to explore and compare solution algorithms that are most efficient for the proposed mathematical models.
- Task 5: Numerical study (2 months). We will conduct several numerical studies to demonstrate the proposed methodology. Sensitivity analyses will be conducted to assess the impact of different factors on the equity and efficiency of wireless charging lane deployment.
- Task 6: Report writing (2 months).

Project Cost

Total Project Costs:	$180,000
MPC Funds Requested:	$ 90,000
Matching Funds:	$ 90,000
Source of Matching Funds:	Utah LTAP, financial support

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