ON THE OPTIMIZATION OF ELECTRIC CHARGING INFRASTRUCTURE TO ADDRESS VEHICULAR EMISSIONS

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1 Introduction

Greenhouse gas (GHG) emissions are a main cause of climate change (IPCC 2007). Global efforts to reduce GHG emissions have intensified by increasing the production of electric vehicles (EVs). To promote EVs, the objective of this study is to identify the optimal location of static charging stations on a road network. The facility location problem in traffic networks has been widely investigated in several studies. In the context of locating electric charging stations, the literature can be classified into two groups. The first addresses locating electric charging station location where link travel times are assumed constant (Huang et al. 2015; Wang et al. 2016). These studies are more appropriate for intercity trips where travelers' route choices do not have a significant impact on the travel times. The second group (e.g. He et al. 2013; Liu and Wang 2017) addresses electric charging station location at metropolitan areas with consideration of congestion effects and travelers' route choices. This study falls into the latter group as it seeks to optimally locate electric charging stations while considering traffic congestion.

This study's facility-location based framework can facilitate the transition toward full adoption of EVs. This enables the transport decision-maker to adopt policies that promote environmentally sustainable transportation systems with respect to vehicular emissions. Specifically, transport decision-makers need to gradually prepare the infrastructure. In the context of vehicle fuel, the goal is to gradually change gas stations to electric charging stations. The contributions of this study are threefold. First, it is the first study that considers ICEV refueling needs as part of the phased-transition plan toward fully adopting EVs over a planning horizon. Therefore, the study also incorporates the gradual conversion of existing gas refueling stations into electric charging stations. This is an important equity issue. Second, this study adopts an objective of minimizing vehicular emissions as a basis for developing the optimal schedule for constructing

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EV charging stations. Third, in developing the EV charging station decisions, this study considers two key aspects related to the expected technological advancement of EVs over the planning horizon: EV driving range and EV extra ownership cost. To do this, the study assumes that the driving range of EVs varies over the planning horizon. It also considers the time-dependent additional cost of EVs relative to ICEVs because the EV purchase cost is expected to reduce over time due to technological advancement and scale economies of EV production.

2 Methodology

In this section, we formulate the electric charging station location problem as a bi-level program. Fig. 1 presents the structure of bi-level problem. In the upper-level, the transport decision-maker goal is to minimize the vehicular emissions. The control decisions for transport agency decision-maker and private-sector investor are the locations of electric charging stations and operating capacities. These decisions are subject to budget constraints for each period of the planning horizon. The electric charging and refueling stations capacities should be sufficient to address the need of travelers. At the lower level, travelers aim to address their travel needs while minimizing their travel costs. The control decisions for travelers are to select the route and vehicle type (EV vs. ICEV). When the transport decision-maker promotes the construction of EV charging stations or re-purposing of existing gas refueling stations, ICEV and EV travelers respond by purchasing EVs and changing their routes to reduce their travel times on trips that involve refueling/recharging. The duration of each period is sufficient for travelers to switch from an ICEV to EV. At user equilibrium condition, travelers are unable to further reduce their travel times by unilaterally changing their routes.

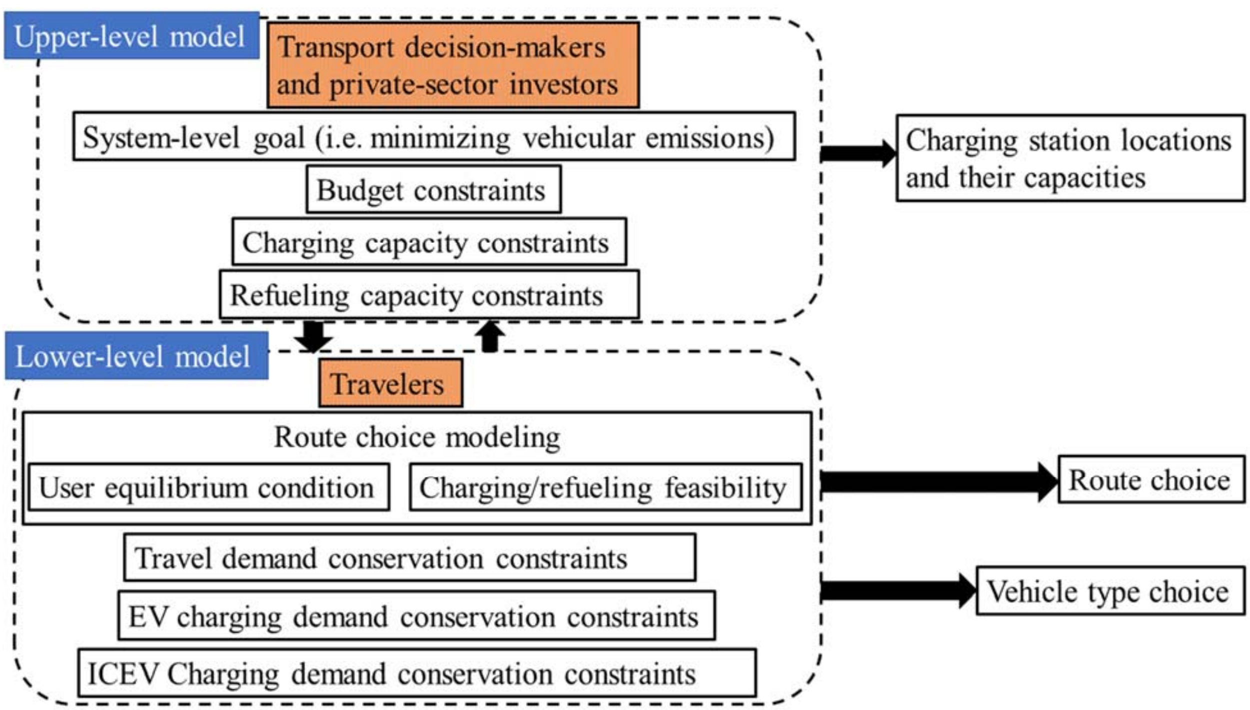

Fig. 1. **The bi-level nature of the problem context**

3. Numerical experiments

In this study, we carried out computational experiments to demonstrate the applicability of the proposed model. The electric charging location problem is solved for the Sioux-Falls network within five periods. The candidate nodes for locating a charging station are shown in orange and yellow in Fig. 2.

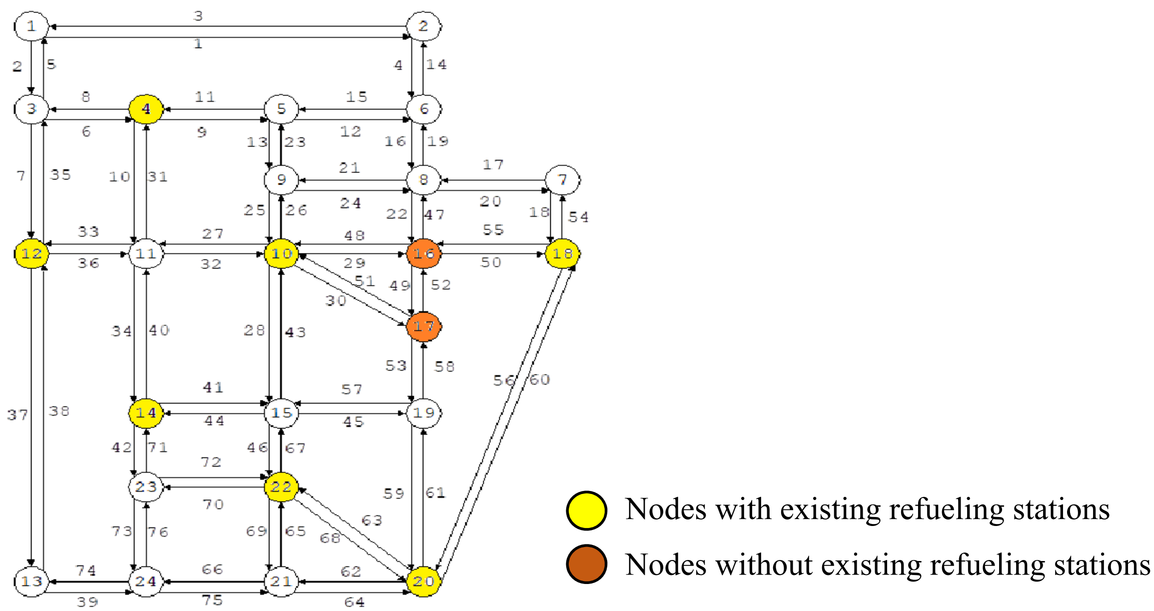

Fig. 2. Sioux-Falls network with candidate charging station locations.

Fig. 3 illustrates the impact of the transition process toward the EV adoption on the average travel costs of ICEVs with refueling need. To understand the impact, we compare the travel costs of ICEV with refueling need under two cases, (i) without EVs (case 1), (ii) with EVs under low budget scenario (case 2) and (iii) with EVs under high budget scenario. The ICEV average travel costs are higher under case 3 compared to cases 1 and 2. The ICEV average travel time increases under cases 1 and 2. It is due to growth in travel demand during the planning horizon. Under case 3, the ICEV average travel time increases in periods 2 and 3 where it is 8 percent higher under case 3 compared to case 1 in period 3. This is due to the fact allocating high budget to minimize vehicular emissions and promote EVs by changing existing refueling stations leads to lesser accessibility to refueling stations for ICEVs. This analysis shows the importance of using a phased and gradual strategy for EV station investment, to be consistent with the objective of facilitating a smooth transition to EVs; this is because a drastic and sudden reduction in the number of gas stations will tremendously increase ICEV travel costs which makes it unsustainable in practice.

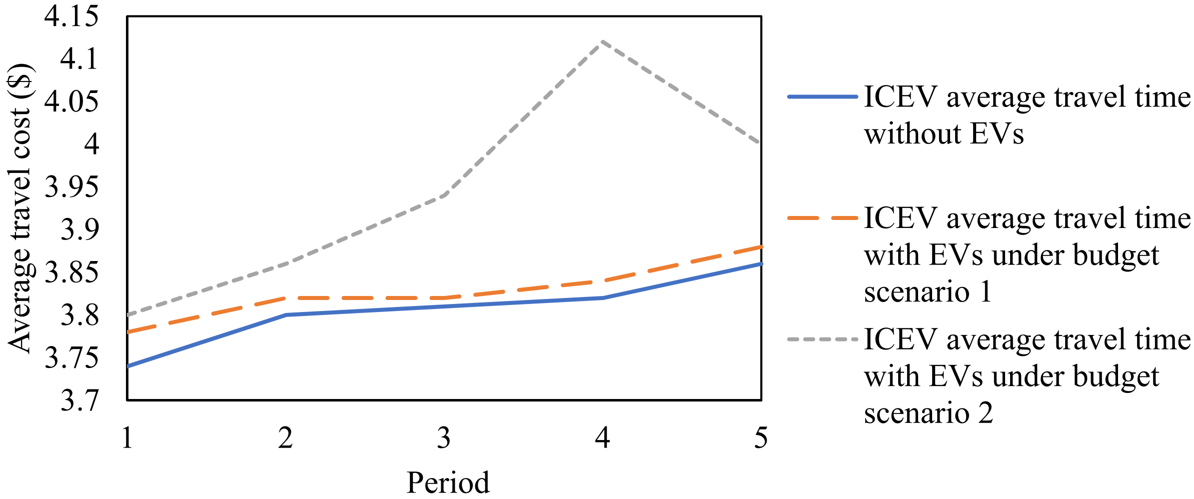

Fig. 3. Impact of Electric Charging Station Construction Budget on Average Travel Costs of ICEVs with Refueling Need

3 Concluding Remarks

This study proposed a comprehensive framework for strategically scheduling EV charging stations within a long-term planning horizon and a specified budget with the goal of minimizing vehicular emissions at urban areas. The optimization problem is formulated as a bi-level model. At the upper level, the transport agency decision-maker and the private sector make the optimal decision regarding the number, locations, and capacities of the needed electric charging stations. Based on the decisions made at the upper level, travelers (at the lower level) decide on their choices of route and vehicle type (EV vs. ICEV). The bi-level model is solved using an active-set algorithm. The numerical experiments demonstrate that if the transport decision-maker allocates sufficient budget to increase the accessibility of electric charging stations, it can significantly increase the EV market penetration and reduce vehicular emissions through the planning horizon. Further, it is demonstrated that with the technological advancements, transport decision-makers will need to invest progressively lower amounts of funds to satisfy the needs of travelers in the charging network.

This research can be extended in several directions. First, this study only considers ICEVs and EVs. However, plug-in hybrid vehicles (PHEVs) can both recharge at electric charging stations and refuel in gas stations. Hence, they can play an important role in this transition phase toward adopting EVs and hence, it is vital to consider them in the proposed framework. Second, this study assumes zero delay for charging and refueling of EVs and ICEVs, respectively. However, this assumption needs to be relaxed in future studies as the charging delay of EVs currently is significantly higher compared to the refueling delay of ICEVs. This can affect the decision of travelers regarding their route and vehicle type choices.

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