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Optimal scheduling of a taxi fleet with mixed electric and gasoline vehicles to service advance reservations

Chung-Cheng Lu[a], Shangyao Yan[b,*], Yu-Wei Huang[b]

[a] Department of Transportation and Logistics Management, National Chiao Tung University, Hsinchu 300, Taiwan
[b] Department of Civil Engineering, National Central University, Taoyuan 320, Taiwan

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ABSTRACT

This study addresses the problem of scheduling a fleet of taxis that are appointed to solely service customers with advance reservations. In contrast to previous studies that have dealt with the planning and operations of a taxi fleet with only electric vehicles (EVs), we consider that most taxi companies may have to operate with fleets comprised of both gasoline vehicles (GVs) and plug-in EVs during the transition from GV to (complete) EV taxi fleets. This paper presents an innovative multi-layer taxi-flow time-space network which effectively describes the movements of the taxis in the dimensions of space and time. An optimization model is then developed based on the time-space network to determine an optimal schedule for the taxi fleet. The objective is to minimize the total operating cost of the fleet, with a set of operating constraints for the EVs and GVs included in the model. Given that the model is formulated as an integer multi-commodity network flow problem, which is characterized as NP-hard, we propose two simple but effective decomposition-based heuristics to efficiently solve the problem with practical sizes. Test instances generated based on the data provided by a Taiwan taxi company are solved to evaluate the solution algorithms. The results show that the gaps between the objective values of the heuristic solutions and those of the optimal solutions are less than 3%, and the heuristics require much less time to obtain the good quality solutions. As a result, it is shown that the model, coupled with the algorithms, can be an effective planning tool to assist the company in routing and scheduling its fleet to service reservation customers.

1. Introduction

1.1. Background and motivation

The past decade has witnessed the trend of replacing conventional internal combustion engine (ICE) or gasoline vehicles (GVs) with alternative fuel vehicles (AFVs) or electric vehicles (EVs) to reduce greenhouse gas (and air pollution) emissions and energy consumption from the transportation sector (e.g., Buekers et al., 2014; Fernandez et al., 2011; Yuksel and Michalek, 2015). Advanced AFV or EV technologies have been applied not only to private passenger cars but also commercial motor vehicles, such as trucks, buses and taxis.

Taxis are one of the most common personalized modes of transportation in many cities, thus the expansion of EVs to taxi fleets has several benefits. Because taxis operate primarily in areas with high population density, the deployment of EV taxi fleets could significantly reduce emissions, pollutants and noise which are harmful to public health in densely populated urban areas (Buekers

* Corresponding author.
E-mail address: t320002@cc.ncu.edu.tw (S. Yan).

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et al., 2014). Many cities have recently started electric taxi pilot projects (e.g., McDonald, 2016). Tokyo, Japan was one of the first big cities that experimented converting gasoline taxis to EV taxis (Kim, 2010), followed by other trial programs in a number of major cities, such as New York City, USA (NYC, 2010; Gordon-Bloomfield, 2013), Montreal, Canada (McDonald, 2016), Nanjing, China (Yang et al., 2016, 2017), Seoul, Korea (Kim et al., 2017), and Shenzhen, China (EVN, 2010).

Success in replacing existing GV taxi fleets with EVs depends on several important tasks. In addition to securing the (financial) investment to ease the costs for taxi companies, government support policies (e.g., regulations and subsidies), adequate charging infrastructure and battery technology are all critical to promote market acceptance of EV taxi fleets (e.g., Kim et al., 2017; Peterson and Michalek, 2013; Xi et al., 2013; Zhang et al., 2012). Recognizing that there are obstacles for the deployment of large-size EV taxi fleets (or replacing an entire fleet with EVs), such as the large capital investment, limited driving range and inadequate coverage of charging stations, most of the aforementioned pilot projects have started with just a few EV taxis. Hence, it is assumed that taxi companies may operate their fleets with both GV and EV vehicles during the transition from GV to (complete) EV taxi fleets.

Travel requests by customers for taxis can be generally divided into two categories: current and advance (e.g., Wang and Cheu, 2013; Wang et al., 2016). Current requests are those that require vacant taxis to service them as soon as possible within a short period of time (e.g., 30 min), while advance requests are typically made a certain amount of time beforehand. In this paper, the focus is on advance reservations. In practice, most taxi companies determine the schedule or routing of taxis to service advance reservations using manual methods, which may result in inefficient use of the taxi fleet. Moreover, to the best of our knowledge, there are no studies in the existing literature addressing routing or scheduling problems for a taxi fleet with both EVs and GVs. The above practical concern and this gap in the literature have motivated us to deal with the scheduling problem of a taxi fleet with mixed EVs and GVs to service advance reservations. This problem is called the mixed taxi fleet scheduling problem (MTFSP) hereafter in this paper.

A number of critical but challenging modeling issues need to be addressed to develop the optimal scheduling model for the mixed taxi fleet:

(i) The distinct operating characteristics of the EVs and GVs make it difficult to develop an integrated modeling framework that can effectively describe various activities for both types of vehicles. In particular, due to limited range of EVs, the proposed model should not only be able to keep track of the trajectory and the remaining electricity level of each EV taxi but also be able to determine the optimal time and place for charging. Needless to say, these requirements do not apply to GV taxis, because their driving range is much longer than that of EV taxis.
(ii) While the scheduling problem of a taxi fleet composed of only EVs or GVs may be viewed as the vehicle routing/scheduling problem with *paired* pickup and delivery (VRPPPD), simultaneously determining the optimal schedules for a fleet comprising both GV and EV taxis is a much more complex problem that involves the VRPPPD with heterogeneous vehicles.
(iii) Given the goal of reducing carbon emissions and energy usage, EVs should be given priority to service travel requests. Only when the number of EVs is insufficient to satisfy all the requests, will GVs be assigned to service some of them. The proposed model should incorporate an incentive to ensure that priority is yielded to EV taxis (or a penalty to discourage the use of GVs).

1.2. Literature review

Problems related to EV and AFV taxis have received increasing attention from researchers and practitioners around the world. As the deployment of EV taxi fleets is still in the early stages, several studies have been carried out examining the feasibility and validity of switching from GV to EV taxis. For instance, Yang et al. (2016), utilizing vehicle trajectory data collected by onboard global positioning system (GPS) units, investigated the market potential and environmental benefits of replacing GVs with EVs in a taxi fleet in Nanjing, China. Zou et al. (2016) analyzed the energy consumption and efficiency of EV taxis using the operational data collected from two EV taxi demonstration projects in Beijing, China. Kim et al. (2017) analyzed the potential for adoption of electric taxis using actual digital tachometer data from Seoul, Korea, confirming the financial feasibility and environmental benefits of implementing electric taxis. Hu et al. (2018) analyzed battery electric vehicle feasibility from taxi travel patterns in New York city.

Considering that adequate charging infrastructure is critical for the deployment of EV taxi fleets, a number of studies have proposed methods to determine the optimal number, location and size of EV taxi charging stations. For example, Sathaye (2014) provided an optimization framework for the design of an electric taxi system, and an assessment of optimal costs associated with various options. Tu et al. (2016) developed a spatial–temporal demand coverage approach to optimize the locations of electric taxi charging stations. Yang et al. (2017) presented a data-driven optimization-based approach to allocate chargers for EV taxis throughout a city in China with the objective of minimizing the infrastructure investment. Chen et al. (2017) investigated the problem of deploying both stationary and dynamic charging infrastructure for electric vehicles along traffic corridors. He et al. (2018) presented an optimal charging station location model with the consideration of electric vehicle's driving range. Loeb et al. (2018) conducted agent-based simulations with shared autonomous electric vehicles (SAEV) modeling as a new mode. They analyzed performance characteristics of SAEV fleets serving travelers across the Austin, Texas network, and suggested that the number of station location depends almost only on vehicle range.

Very few studies have considered the operational management, such as dispatching, routing and scheduling, of EV taxi fleets. Lu et al. (2012) proposed a dispatching strategy with charging plans based upon client requests for a commercial fleet purely composed of electric taxis. Their strategy considered the demand, the remaining power of electrical taxis, and the availability of battery charging/switching stations in order to lower the waiting time for recharging and thus increase the workable hours for taxi drivers. Wang and Cheu (2013) addressed the routing problem of a taxi fleet that uses EVs to cater solely for trips with advance reservations. The idea was to link multiple trips to form a route which would then be offered to a taxi driver. The problem was formulated as a