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Operations of electric taxis to serve advance reservations by trip chaining: Sensitivity analysis on network size, customer demand and number of charging stations

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ABSTRACT

This research investigated the performance of an Electric Taxi (ET) fleet that catered solely for customers with advance reservations. In a previously related research, a customized Paired Pickup and Delivery Problem with Time Window and Charging Station (PPDPTWCS) had been formulated to solve for the minimum number of taxis that would serve a fixed set of customer demand. The concept behind this fleet optimization was to chain multiple customer trips and trips to Charging Stations (CSs) to form a route and assigned to a taxi driver. In this paper the sensitivity of the ET fleet's operations with respect to network sizes, customer demand densities and number of CSs have been investigated. It also analyzed the market shares of the CSs and the occupancy of a CS over time. The results showed that, (1) the expansion of network size or the increase in customer demand density led to increase in fleet size, number of trips to the CSs and maximum occupancies at the CSs but these performance measures grew at different rates; (2) when the network size and number of CSs were fixed, an increase in customer demand density led to a better utilization of taxis in terms of more customers served per taxi and higher average revenue per taxi; (3) given the same network size and demand density, the ET fleet's performance was relatively insensitive to the number of CSs; and (4) the usage of individual CS was affected by the number of CS and their locations; and (5) when all the ETs were fully charged at the beginning of the same shift hour, they visited the CSs in bunches when their batteries were about to run out. These findings contribute to a better understanding of the operations of the ET fleet and the CSs. They could be used for making better decisions in the planning of ET operations.

Introduction

Taxis play an important role in offering a personalized transportation mode. Taxis that are Elective Vehicles (EVs) are more and more commonly known as Electric Taxis (ETs). The term electric taxi and its acronym ET are used for the rest

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of this article. Cities such as Amsterdam, Bogota, London, Montreal, San Francisco and Shenzhen have been promoting ETs (FleetCarma, 2016).

EVs offer benefits such as zero emission and little engine noise. However, compared to gasoline-powered vehicles that could be refueled quickly, batteries in EVs could not be fully charged in a few minutes. Depending on the battery technology and charging method, an EV's battery may take several hours to be fully charged (Zhou et al., 2015). Because EVs have limited running range before their batteries need to be charged, they are used mainly for inner-city transport, such as the taxi business. There are about 462,000 EVs in the world in 2015 and this figure is forecasted to increase to 41 million by 2040 (Bloomberg, 2016). As for ETs, the world market is expected to grow by 33% per year from 2013 to 2018 (Urban Foresight, 2014). Another forecast has estimated that there will be 260,000 ETs in major cities in the world in year 2020 (EVsRoll, 2012).

The idea of this research came from the taxi operations in Singapore. With the high cost of private vehicle ownership, taxi is a popular transportation mode in Singapore. To compete for customers, all the taxi companies in Singapore equip their taxis with Global Positioning System (GPS) based dispatch systems. There are two categories of taxi reservations in Singapore: current and advance. Current reservations are those in which customers request vacant taxis to reach them within 30 min. Conversely, advance reservations are requests made by customers at least 30 min ahead of pickup times. The focus of this paper is on advance reservations. Gasoline or diesel engines currently power almost all the taxis in Singapore. This research studies the scenario if a taxi company switches its fleet to ETs to serve customers with advance reservations, but faced with the constraints of maximum battery running time and minimum battery charging time.

This research built on an earlier work (Lee et al., 2004) which introduced the Singapore Taxi Advance Reservation (STAR) problem and its solution algorithms. The STAR problem is based on a taxi system with all gasoline-powered vehicles. With the hypothetical scenario of ETs that make up the entire taxi fleet (at least those taxis that are dispatched to serve trips with advance reservations), this problem has been reformulated as the Singapore Taxi Advance Reservation with Electric vehicles (STARE) problem (Wang and Cheu, 2013). The difference between STAR and STARE problems is that in the STARE problem, taxis frequently need to be charged at EV's Changing Stations (CSs). When presenting the STARE problem and its solution algorithm, Wang and Cheu (2013) studied the sensitivity of the ET system's operations with respect to the maximum battery running time, charging time and different number of CSs.

This research continued to focus on the STARE problem and conducted sensitivity analysis with respect to network size, customer demand density and different number of available CSs. It also analyzed the market shares of the CSs and occupancy of a CS over time. Although the investigated problem is inspired by the Singapore's taxi dispatch system, the findings are applicable to any cities that use ETs to serve trips with advance reservations. This research provides taxi system designers and planners insights on how the network size, customer demand, number and location of CSs will impact the system performance of taxi and CS operations. The designers and planners can make use of the findings to make decisions on the service coverage area (network size) and/or number and locations of CSs, when the customer demand fluctuates.

The paper is organized as follows. Following this introduction, a brief description of the existing taxi dispatch system in Singapore is described. The concept of trip chaining is next presented. This is followed by the descriptions of the STAR and STARE problems, and their solution algorithms. The experiments are subsequently presented, which include a comparison of the solutions of the STARE problem with different network sizes, demand densities, number of CSs, market shares and CS occupancy.

Review taxi operations and related research

Taxi dispatch system in Singapore

In Singapore's taxi industry, taxi companies own the vehicles. Each taxi is rented to three drivers who operate in three shifts in a day. The shift hours are fixed, i.e., all the taxis in the company start and end their shifts at the same time. Drivers rent taxis from the companies by paying fixed daily fees. The companies maintain the vehicles but the drivers are responsible for refueling and the cost of the fuel. All the taxis subscribe to, and are part of the company's dispatch system. When a customer requests for a taxi in advance either by phone or by the internet, the company's dispatch center broadcasts the trip information immediately to all the taxis (with and without passenger) in its fleet. It is up to the taxi drivers to decide if they want to bid to serve this customer. Drivers do not have to pay for the bid. The dispatch system assigns this trip to the first driver who bids for it, regardless of the taxi's location. Under this taxi ownership-rental arrangement and dispatch policy, there is no consideration of fleet size and revenue optimization. Taxi companies prefer to increase the number of taxis rented to drivers, as each taxi guarantees a fixed rental revenue per day. In addition, under the existing bidding policy, there is no optimization of the taxi's occupancy rate. That is, up to 100 different taxis might be dispatched to fulfill an equal number of customers. It is up to the taxi drivers to plan their activities within a shift to earn fare revenue.

There are two types of taxi reservation: current and advance. Current reservations are trips that require pickups within 30 min of making the requests. Advanced reservations are trips that are requested by customers more than 30 min ahead of pickup times. The acceptance of an advanced reservation trip usually affects a taxi driver's behavior in serving customers (at the time window before the committed pickup time). A taxi driver often faces a dilemma when the time is approaching for him/her to pick up a customer who has made an advance reservation. If the driver picks up a street hailing passenger,