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The optimal design and cost implications of electric vehicle taxi systems

Nakul Sathaye

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ABSTRACT

In recent years, taxis in multiple cities and metropolitan areas around the world have shifted to utilizing alternative fuel options. Such change has significant potential to reduce environmental externalities and can contribute to alleviating energy policy concerns. However, little work has been conducted to assess the tradeoffs between selecting various fuels for taxis, or to design alternative fuel taxi systems. These tradeoffs exist as a result of the differing costs associated with fleet replacement, infrastructure deployment, operations and maintenance decisions, and costs to users. This paper aims to address this issue by providing an optimization framework for the design of electric taxi systems, and an assessment of optimal costs associated with various options. We focus on comparing the costs of taxi systems made up of gasoline vehicles, hybrid-electric vehicles, plug-in hybrid electric vehicles with AC Level 2 infrastructure, electric vehicles with battery switching infrastructure, and electric vehicles with DC Level 2 fast charging infrastructure. This approach is based on transit systems design methods and focuses on developing an approximate analytic model for electric taxi systems, which can be expanded upon in future research, to address large-scale taxi systems design problems. Scenario results are presented for various city types.

1. Introduction

In recent years, taxis in multiple cities and metropolitan areas around the world have shifted from utilizing gasoline and diesel vehicles to alternative fuel options such as natural gas, hydrogen and electricity (Baptista et al., 2011; Gao and Kitirattragarn, 2008; Reynolds et al., 2011). Such change has significant potential to reduce environmental externalities and can contribute to alleviating energy policy concerns. However, little work has been conducted to assess the tradeoffs between selecting various fuels for taxis, or to design alternative fuel taxi systems. There exist tradeoffs as a result of the differing costs associated with fleet replacement, infrastructure deployment, and ongoing operations and maintenance.

This paper aims to address this issue by providing an optimization framework for the design of alternative fuel taxi systems, and an assessment of optimal costs associated with various fueling options. The optimization framework is based on previously developed methods used for transit systems design (Daganzo, 2010, 1978), and we focus on comparing the costs of taxi systems that have internal combustion engine vehicles (ICEV), hybrid-electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) with AC Level 2 charging infrastructure, battery electric vehicles (BEV) with battery switching infrastructure, and BEVs with DC Level 2 fast charging (DCFC) infrastructure (SAE International, 2011). The optimization framework provides a basis for solving larger real-world electric taxi systems design problems in the future.

E-mail address: nakulsathaye@gmail.com

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This paper differs from other studies of taxi systems in three ways. First, most other studies have typically assessed taxi problems by applying economic models to determine the optimal number of taxis in a supply–demand equilibrium framework (Salanova et al., 2011). The impetus for these approaches was the significant deregulation that occurred internationally in taxi markets starting approximately in the 1970s. However, in practice, complete deregulation results in significant problems, in turn causing many cities to return to some form of fare regulation and limitation of the number of operating taxis (Schaller, 2007). The economic models have been developed to account for a host of factors including taxi markets with search frictions, endogenous service intensity, and demand elasticity (Yang and Yang, 2011).

Daganzo (2012) shows that the joint demand estimation/pricing/design optimization problem for infrastructure systems can be simplified by being broken into its components, while still allowing for welfare maximization. In this context, the previous economic modeling literature for taxi systems addresses the demand estimation and pricing components. We address the design optimization component in this paper. Therefore, the approach in this paper can be used to complement the previously mentioned economic models.

The second characteristic, which differentiates this paper from most other studies, is that we focus on comparing the costs and design of alternative fueling options for taxi systems. In particular, we compare vehicles that are powered by conventional fuels versus electricity. This requires an assessment both of taxi operations and infrastructure costs, and a method for optimally locating infrastructure. Example scenarios are provided for various city sizes and taxi systems having different vehicle types in Section 4, and the approach can be built upon to optimally locate infrastructure for large-scale problems. The only other study, to the author's knowledge, which focuses on electric taxi operations is Carpenter et al. (2013), which provides a case study of a taxi system with assumptions about hypothetical battery switching activity. This study takes a simulation-based approach to modeling taxi operations.

This relates to the third differentiating characteristic of this paper, which is that we develop an approximate analytic model for optimal taxi system design, based on the approach in Daganzo (1978), which can also be built upon to address larger problems. This differs not only from exact simulation studies, but also from network-based approaches (e.g. Yang and Wong (1998) and many insightful references in Yang and Yang (2011)). While these types of approaches can make predictions to a high level of detail, they can be impractical for large-scale problems, as stated in Daganzo (2007) for transportation forecasting models more generally. Similar to Daganzo (2007), we may categorize three main reasons that these previous approaches can be impractical: (i) the models require too many inputs and can, in turn, be computationally burdensome; (ii) decisions related to driver navigation, searching by passengers and drivers, and charging location and timing can be difficult to predict in detail; (iii) oversaturated traffic networks behave chaotically, which can make taxi operations during peak hours, which are often of greatest interest, difficult to predict.

Simulation models are especially susceptible to (i), although aspects of (ii) and (iii) might be predicted well with sufficient data. Nevertheless, aspects of (ii) may be difficult to predict when modeling new and evolving technologies, due to a lack of existing data. Network-based approaches can also be susceptible to (i) for large problems, due to need to account for numerous nodes and links. In addition, network-based approaches make assumptions about driver behavior which may not be representative of real-world behavior, creating problems related to (ii). Regarding (iii), network-based approaches may also not be well-suited to making predictions, since they often rely on unrealistic assumptions about congested networks (Daganzo, 2007).

Therefore, while simulations and network-based approaches can be useful for some problems, we utilize an approximate approach, since it allows for a concise, but relevant analysis of real-world problems. Such modeling flexibility is especially important for transportation systems design problems that involve evolving technologies, so that they can be implemented adaptively. Adaptation is important when implementing novel infrastructure technologies, since demand can be difficult to predict (Brownstone et al., 2010). Similar arguments have been made for the analysis of a variety of transportation problems (Daganzo et al., 2012) and previously for electric vehicle infrastructure deployment (Sathaye and Kelley, 2013). Nevertheless, it should be noted that approximate models must be specified carefully so that there is no loss of relevant information. Therefore, it is important to note that other modeling approaches, especially simulations, can help in validation.

Section 2 presents background information of vehicle types and their refueling characteristics, definitions for terms used in the taxi systems models of Section 3, and general model assumptions. In addition, Section 2 compares the modeling assumptions in this paper to previous approaches. Section 3 presents the optimization methodology, which is applied in Section 3 using various city forms and vehicle types. Section 5 provides a discussion of modeling assumptions, additional optimization model features, implementation considerations, and policy implications. Section 6 concludes the paper.

2. Background

2.1. Vehicle types and characteristics

As a preface to the models in Section 3, we describe the various vehicle types considered (ICEV, HEV, PHEV and BEV), and how their characteristics affect model development.

ICEV represents vehicles that are powered by a conventional internal combustion engine, typically using fossil fuels such as gasoline or diesel. Range limitations are not generally a concern for these vehicles, since the size of the fuel tank typically allows for a taxi driver to complete a full shift without having to refuel.