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Taxi market equilibrium with third-party hailing service

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ABSTRACT

With the development and deployment of new technologies, the oligopolistic taxi industry is transforming into a shared market with coexistence of both traditional taxi service (TTS) and app-based third-party taxi service (ATTS). The ATTS is different from TTS in both entry policy and fare setting, and brings competition into the market. To account for the revolution of the taxi industry, in this study, we analyze the characteristics of the TTS and ATTS, model the taxi market as a multiple-leader-follower game at the network level, and investigate the equilibrium of taxi market with competition (TMC Equilibrium). In particular, passengers are modeled as the leaders who seek to minimize their travel cost associated with taxi rides. Followers involve TTS and ATTS drivers, who compete for passengers to maximize their revenue. The network model captures selfish behavior of passengers and drivers in the taxi market, and we prove the existence of TMC Equilibrium for the proposed model using variational inequality formulations. An iterative algorithm is further developed to find the TMC Equilibrium, which corresponds to the strongly stationary point of the multi-leader-follower game. Based on numerical results, it is observed that fleet size and pricing policy are closely associated with the level of competition in the market and may have significant impact on total passengers cost, average waiting time, and fleet utilization.

1. Introduction

Urban taxi offers great flexibility and mobility via its door-to-door service and 7/24 availability, and plays an important role in urban transportation system. By the end of 2014, there were over 50,000 taxi drivers serving 600,000 passengers daily in New York City (NYCTLC, 2014). Moreover, in other large cities such as Tokyo and Paris, there is one taxicab per hundred population (Consultant, 2014). In light of the size and significance of urban taxi industry, framing regulation policies is of key concern for stakeholders in order to correct market imperfection (Schaller, 2007) and maintain level of service. To help frame regulations, economists have developed aggregate demand and supply models to examine the effectiveness and consequences of policies mainly associated with entry and fare controls (Douglas, 1972; De Vany, 1975; Beesley and Glaister, 1983; Häckner and Nyberg, 1995; Cairns and Liston-Heyes, 1996; Shreiber, 1981; Dempsey, 1996; Çetin and Yasin Eryigit, 2011). Nevertheless, as suggested by Yang and Wong (1998), since taxi service takes place over space, aggregate models are oversimplified, and are incapable of capturing the influence of road network structure and the equilibrium nature of taxi service. This motivates to model taxi service at the network level.

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The first work which models urban taxi service at the network level was exemplified by Yang and Wong in 1998 (Yang and Wong, 1998), where a network model was developed to characterize the movement of vacant and occupied taxis on the network. It was assumed that passengers will always receive the service and any driver will eventually find a passenger, and taxi waiting time and utilization rate were analyzed with the change of taxi fleet size. Based on the network model, Wong and Yang developed an efficient algorithm to solve the taxi network movement problem as an optimization problem Wong and Yang (1998), Wong et al. (2001) improved the model by incorporating network congestion and demand elasticity, Wong et al. further proposed a sensitivity-based solution algorithm to solve their congestion model more efficiently (Wong et al., 2002), and the basic taxi network model was implemented to study how different regulations may affect the demand-supply equilibrium (Yang et al., 2002). While drivers' behavior is the main focus of the aforementioned studies, Yang et al. (2010) proposed to model the behavior of drivers and passengers jointly, where the Cobb-Douglas function (Varian, 1992) was implemented to characterize trip waiting time as a function of the choices made by passengers and drivers. While the taxi service model (Yang and Wong, 1998) serves as the base for all these studies, they are observed to share two fundamental assumptions: (1) the taxi service is well-regulated and the market is monopolistic, and (2) all passengers will be serviced and all drivers will eventually find a trip during the modeling period.

However, as Uber launched their transportation service in 2009, it breaks the convention of traditional taxi service (TTS), where street hailing is the main way of getting a taxi ride. Instead, it offers app-based third-party taxi service (ATTS), which allows passengers to request taxi service using smartphones. In a few years, we have witnessed the revolution of taxi industry globally with the entrance of other ATTS providers such as Lyft and Didi, and the market property has been complicated as it transforms from oligopoly to shared economy. Consequently, to understand the nature of the new market, there is an emerging need of a network model which accounts for the coexistence of TTS and ATTS. And modeling the market with TTS and ATTS is the objective of the study.

Specifically, the importance of the study can be understood from two aspects. First, the entrance of ATTS provides passengers with an alternative taxi service, and therefore introduces competition into the market. Therefore, it is no longer appropriate to model taxi service as monopolistic, and we need to develop new methodologies to account for the consequence of competition in the market and investigate the equilibrium of taxi market with competition (TMC Equilibrium). Second, within 5 years, Uber has attracted over 8,000,000 users globally, and is serving 400 cities, with 50,000 new drivers added monthly (DMR, 2015). Meanwhile, similar ATTS providers emerge all over the world and become legitimate in more and more cities. Admittedly, ATTS is becoming indispensable in taxi market, and caution should be exercised as how to regulate the market with both TTS and ATTS appropriately. This in return requires a model to analyze the impact of different regulation strategies on the market.

To model the taxi market with TTS and ATTS, it is essential to understand the underlying differences between TTS and ATTS. Unlike TTS, which mainly serves passenger via street hailing, ATTS offers rides through smartphone apps, which helps to narrow the information gap between passengers and drivers. Operationally, there are two major differences between TTS and ATTS. First, as a revenue-driven business, ATTS will charge passengers premiums on top of the time-distance based fare setting when there is high level of demand. This indicates that ATTS is not regulated in terms of pricing policy. Second, a smartphone may turn any licensed car owner into an ATTS driver. Hence, there is no restriction on the fleet size of ATTS and drivers have the freedom to join or leave the market at anytime. Moreover, due to joint-effect of the two properties, ATTS drivers are observed to join the market strategically based on the amount of premiums, known as 'chasing the surge' (Cook, 2015). On the contrary, TTS drivers purchase the medallion to enter the market, and usually keep running for their entire shift in order to compensate the entry cost and make revenue.

In this paper, we build the taxi network model for the coexistence of TTS and ATTS. In particular, the interactions among passengers, TTS drivers and ATTS drivers are mathematically formulated as a taxi market multi-leader follower game (TM-L/F game), and passenger equilibrium and driver equilibrium are modeled as generalized Nash equilibrium problems (GNEPs). For the GNEPs, passengers choose from TTS and ATTS to minimize their trip cost. And TTS and ATTS drivers need to decide where to pick up the next passengers to maximize their revenue. The study contributes to the literature in the following ways: (1) a network service model is formulated to characterize passenger and driver behavior in the taxi market with both TTS and ATTS, (2) competition in the market is modeled as a multi-leader-follower game and the definition of TMC Equilibrium is introduced, (3) the structure of the game is analyzed and variational inequality is used to prove the existence of market equilibrium for the taxi market with competition, (4) an iterative algorithm is developed to find the strongly stationary point of the multi-leader-follower game, and (5) we explore the consequences of change of market attributes including fleet size and pricing policy, and provide insights for regulating the taxi market with competition.

The rest of the paper is organized as follows. Next section introduces mathematical notation and preliminaries of taxi market, followed by formulations of passenger and driver behavior in taxi market with TTS and ATTS. The third section casts the network model into the TM-L/F game, discusses structural properties of the game, and proves the existence of TMC Equilibrium. The fourth part relaxes the GNEPs in both levels of the game as augmented Nash equilibrium problems (NEPs), and presents an iterative algorithm for solving the TM-L/F game. Finally, the numerical experiments are presented and results are discussed, and summary and future studies are provided.