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Dynamic modeling and control of taxi services in large-scale urban networks: A macroscopic approach

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Abstract

Taxis are increasingly becoming a prominent mobility mode in many major cities due to their accessibility and convenience. The growing number of taxi trips and the increasing contribution of taxis to traffic congestion are cause for concern when vacant taxis are not distributed optimally within the city and are unable to find unserved passengers effectively. A way of improving taxi operations is to deploy a taxi dispatch system that matches the vacant taxis and waiting passengers while considering the search friction dynamics. This paper presents a network-scale taxi dispatch model that takes into account the interrelated impact of normal traffic flows and taxi dynamics while optimizing for an effective dispatching system. The proposed model builds on the concept of the macroscopic fundamental diagram (MFD) to represent the dynamic evolution of traffic conditions. The model considers multiple taxi service firms operating in a heterogeneously congested city, where the city is assumed to be partitioned into multiple regions each represented with a well-defined MFD. A model predictive control approach is devised to control the taxi dispatch system. The results show that lack of the taxi dispatching system leads to severe accumulation of unserved taxi passengers and vacant taxis in different regions whereas the dispatch system improves the taxi service performance and reduces traffic congestion by regulating the network towards the undersaturated condition. The proposed framework demonstrates sound potential management schemes for emerging mobility solutions such as fleet of automated vehicles and demand-responsive transit services.

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Keywords: Macroscopic Fundamental Diagram (MFD); Meeting Functions; Multi-user Taxi Market; Multimodal traffic; Receding Horizon

1. Introduction and motivation

Taxi service is a prominent mode of transportation in many major cities by providing a tailor-made and complimentary mobility solution to the public transport system. Despite their popularity, taxis contribute substantially to congestion as they tend to circulate in search of passengers in heavy-demand central business districts. The search

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process is initiated every time a taxi drops off a passenger and becomes vacant. The vacant taxi then cruises to find unserved passengers either in the same zone (where the former passenger was dropped off) or by driving to another zone. The heavy presence of vacant taxi movements is especially overwhelming because it impedes normal traffic and can lead to higher vehicle distance traveled in cities where taxis make up a significant ratio of the traffic mix. (Huo et al., 2012). In New York City, for instance, taxis make up 10% of the transportation mode share with approximately 450,000 taxi trips per day (Taxi and Limousine Commission, 2014). Other cities with moderate levels of taxi traffic are becoming increasingly aware of the future impacts of taxi traffic growth on normal traffic. The City of Toronto, Canada, for instance, estimates to have a total of 2.1 million additional taxi trips by 2022 (City of Toronto, 2016), which requires imposing suitable taxi regulation measures and developing intelligent taxi management systems.

An inefficient taxi service leads to longer vacant taxi travel times, longer passenger waiting times, lower taxi utilization, and traffic congestion. Hence, efficient taxi dispatching should be considered as an imperative part of taxi management systems, which uses real-time information of the fleet to enhance the overall performance of the taxi service. Zhan et al. (2015) showed that taxi dispatch systems, in an ideal case, can reduce the total cost of empty taxi trips by up to 90%. A holistic taxi dispatch system must take into account the interrelated effects of taxis on other traffic modes, and vice versa, while optimizing a network-wide objective criterion. On one hand, excessive and unwarranted taxi dispatching can further impede mixed traffic flow in cities where taxis make up a substantial ratio of the traffic. On the other hand, taxis (either occupied, vacant, or dispatched) are themselves affected by normal traffic conditions as they can incur a long travel time in presence of traffic congestion. This study proposes a dynamic bimodal traffic flow model and a taxi dispatching system that incorporates the interrelated dynamics of taxis and other transport modes (e.g. personal vehicles) to optimize a desirable network objective, which is assumed to be a weighted measure of several performance indicators such as passenger waiting time (for a taxi), taxi searching time (for an unserved passenger), and total network travel time of personal vehicles and occupied taxis. The presented taxi dispatching control method is robust, computationally tractable, and realistically applicable for taxi regulation that also advances the findings of taxi market analysis.

Taxi regulation has been the subject of many studies as early as the 1970s. The prevalent literature on taxi regulation focuses on finding the optimal fare price and taxi fleet size (Beesley, 1973), modeling the network-wide movement of taxis (Yang and Wong, 1998; Jung et al., 2014; Sayarshad and Chow, 2016), elastic taxi demand (Wong et al., 2001), competitive taxi markets (Yang et al., 2002), stochastic taxi passenger demand (Zhang and Ukkusuri, 2016), taxi mode choice Wong et al. (2008), taxi e-hailing (He and Shen, 2015; Wang et al., 2016), local taxi movements in a cell-based network (Wong et al., 2014), demand-responsive services (Amirgholy and Gonzales, 2016), and analyzing the friction in the taxi-passenger meeting process (Yang and Yang, 2011; Yang et al., 2014; Wang et al., 2016). A common ground among these studies is the equilibrium assumption in the vacant taxi movement decisions. Under equilibrium conditions, each vacant taxi travels to the closest and most profitable zone to search for customers. Consequently, at equilibrium, no vacant taxi can unilaterally change its destination, i.e. the next search zone, for a lower cost. From these studies, only a few consider the interrelated effects of taxis and normal traffic: Wong et al. (2001) developed a bi-level model which characterizes the simultaneous movements of vacant and occupied taxis as well as normal traffic flows, Wong et al. (2008) incorporated mode choice (between taking a taxi or a personal vehicle) in a traffic equilibrium model with taxi flows, and Yang et al. (2014) proposed a bilateral taxi-passenger meeting model while considering the congestion externalities of normal traffic and taxi flows. These studies and taxi equilibrium models in particular, however, fall short in representing the dynamic features of traffic congestion, do not capture the spatiotemporal accumulation of vacant taxis and passengers, and require intensive calibration and estimation of origin-destination trip matrices to derive an equilibrium pattern of link travel times. Moreover, the models of taxi equilibrium pose severe empirical limitations in realistic application as they employ link travel cost functions which cannot specify accurately the inter-day traffic dynamics (Tsekeris and Geroliminis, 2013).

With the recent proliferation of taxi hailing apps, such as Uber-taxi and Didi KuaiDi-taxi, optimization of taxi dispatching plays an important role to efficiently match unserved passengers with vacant taxis. Many of the studies on optimal taxi dispatching address the problem as either a variant of the vehicle routing problem (VRP) (Ghiani et al., 2003; Wong and Bell, 2006; Pillac et al., 2013; Hosni et al., 2014; Jung et al., 2016) or the bipartite graph matching problem (Agatz et al., 2012; Zhan et al., 2015; Nourinejad and Roorda, 2016). Under the VRP formulation, each taxi is assigned to sequentially pick up a number of passengers and under the bipartite graph formulation, each taxi is matched with the closest passenger in its vicinity. Both modeling frameworks can easily take into account