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# Pricing scheme design of ridesharing program in morning commute problem ☆

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This paper examines the dynamic user equilibrium of the morning commute problem in the presence of ridesharing program. Commuters simultaneously choose departure time from home and commute mode among three roles: solo driver, ridesharing driver, and ridesharing rider. Considering the congestion evolution over time, we propose a time-varying compensation scheme to maintain a positive ridesharing ridership at user equilibrium. To match the demand and the supply of ridesharing service over time, the compensation scheme should be set according to the inconvenience cost functions and the out-of-pocket cost functions. When the price charged per time unit is higher than the inconvenience cost per time unit perceived by the ridesharing drivers, the ridesharing participants will travel at the center of peak hours and solo drivers will commute at the two tails. Within the feasible region with positive ridership, the ridesharing program can reduce the congestion and all the commuters will be better off. To support system optimum (SO), we derive a time-varying toll combined with a flat ridesharing price from eliminating queuing delay. Under SO toll, the ridesharing program can attract more participants and have an enlarged feasible region. This reveals that the commuters are more tolerant to the inconvenience caused by sharing a ride at SO because of the lower travel time. Compared with no-toll equilibrium, both overall congestion and individual travel cost are further reduced at SO.

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## 1. Introduction

With the development of the urban economy and the growth of population, severe traffic congestion has been observed in many cities, which results in heavy economic losses due to the increase in travel time and energy consumption. Various instruments have been proposed and implemented in order to alleviate congestion, such as congestion pricing and road space rationing. Recently, ridesharing has emerged as an alternative transport mode which can potentially reduce the number of vehicles on the road. The ridesharing platform, e.g., Uber and Lyft, matches drivers and riders in real time and coordinates the drivers to offer rides to travelers with similar itineraries. In return, the passengers will pay compensation to drivers according to pricing scheme provided by the matching agencies. Advanced technologies, such as smartphones and global position systems, enable the system to dynamically match shared rides on very short notice or even en-route

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in practice. Please refer to Agatz et al. (2012) for a comprehensive review in dynamic ridesharing and Furuhata et al. (2013) for an extensive discussion of future research directions.

The ridesharing literature is focused on optimizing the matching problem, i.e., determining the matches between drivers and riders in the system. The optimization models can be categorized according to the objectives. One of the conventional objectives is to minimize total travel distance or total travel time (Agatz et al., 2010, 2011; Wang, 2013). Since the number of matched trips reflects the market penetration of the ridesharing program, some studies aim to maximize the number of the matched trips and participants (Stiglic et al., 2015). The goal of minimizing total waiting time is considered in Guasch et al. (2014). Both Guasch et al. (2014) and Stiglic et al. (2015) explore the effectiveness of using meeting points to facilitate matching. Lee and Savelsbergh (2015) optimize the matching of both ad hoc drivers and dedicated drivers with riders by associating each match with a weight according to its desirability. Herbawi and Weber (2012) study multiple objectives, e.g., maximizing the matched trips, and minimizing the total travel time. There are also other objectives including minimizing total passenger fares (Santos and Xavier, 2013) and the operating cost (Lin et al., 2012).

When the system allows a driver to pick up multiple riders, the simultaneous decisions in matching and routing become the necessary components in ridesharing platform. The similar problem exists in dial-a-ride problem for dispatching taxi service (Dial, 2006), which is essentially a pick-up and delivery problem with time window constraints. However, unlike the dial-a-ride problem in taxi booking, the drivers in ridesharing system may have their own destinations. Wang et al. (2016) extended the pick-up and delivery problem to optimize the routing considering the cost and time saving from High Occupancy Vehicle (HOV) lanes. Similarly, the idea of taxi-sharing is also explored in Ma et al. (2013, 2015) and Hosni et al. (2014). On the other hand, there are studies in facilitating riders to find optimal transfers between drivers, i.e., multi-hop in ridesharing, e.g., see Herbawi and Weber (2011a,b).

There is another stream of literature which examines the commuters' decision making when ridesharing is introduced to the existing road network and the aggregated impacts of ridesharing in traffic congestion (Xu et al., 2014, 2015). By assuming that driver can only pick up riders with same origin-destination (O-D) pair, Xu et al. (2014) extended the traffic assignment model with elastic demand to consider ridesharing as a new mode, and at user equilibrium, nobody can reduce his/her cost by changing route and mode choice. They found that, with a lower ridesharing price, it attracts more ridesharing participants. However, the equilibrium price does not monotonically increase or decrease the congestion level. Xu et al. (2015) relax the same O-D assumption in Xu et al. (2014) and formulate the problem with inelastic demand as a mixed complementarity problem. In their numerical experiments, they conclude that an increase in ridesharing price parameters will increase the number of solo drivers and therefore raise the level of congestion.

This study aims to examine the decision-making of the home-to-work commuters in the morning commute problem with ridesharing program. The analysis of travel patterns in morning commute problem is originated by Vickrey (1969). Given a desired arrival time at the workplace, the commuters choose the departure time from home and make the trade-off between the cost of travel time and the cost of schedule delay (when they cannot arrive at the workplace at the desired time). Accordingly, the temporal evolution of the congestion is explained by the commuters' departure time choices at dynamic user equilibrium at which nobody can reduce his/her own commute cost by unilaterally changing his departure time choice. Vickrey's bottleneck model has been extensively studied to examine the potential impacts of the travel demand management policies (Small, 1982). Small (2015) provides a comprehensive survey of the theory and the applications of bottleneck model in transportation economics. It has been extended to consider user heterogeneity (Cohen, 1987; Arnott et al., 1994; Lindsey, 2004; Small et al., 2005; van den Berg and Verhoef, 2011; Hall, 2013; Liu et al., 2015; Chen et al., 2015; Wang and Du, 2016), elastic demand (Arnott et al., 1993), multiple routes (Amott et al., 1990; Adler and Cetin, 2001; Liu and Nie, 2011), and household activity (Jia et al., 2016). Qian and Zhang (2011) study the morning commute problem in the presence of HOV lanes when there are three modes available: transit, driving alone, and carpool. An extra constant cost is considered by carpool users, caused by the inconvenience at pick-up and drop-off. At static user equilibrium setting, Yang and Huang (1999) examine the design of congestion pricing combined with the operations of HOV lanes in a single O-D network. Konishi and Mun (2010) explore the welfare effects of introducing HOV lanes and converting HOV lanes to HOT lanes when the commuters have different carpool organization costs.

There is limited literature studying the ridesharing problem in the context of time-varying congestion. This paper assumes that, given a fixed total demand, the morning commuters will choose their departure time and mode among the three roles: solo driver, ridesharing driver, and ridesharing rider. Different from the carpool studies, we use a combined time-based and distance-based compensation scheme which is practiced in ridesharing industry. We find that a time-varying ridesharing pricing scheme should be set in order to maintain a positive ridesharing ridership at user equilibrium, depending on the costs of inconvenience and the out-of-pocket costs for ridesharing drivers and riders. Otherwise, the mismatch between the supply of ridesharing service and the demand of ridesharing service over time will occur, and nobody will choose ridesharing at the user equilibirum. In the presence of ridesharing program, the overall congestion is reduced given the proposed ridesharing pricing scheme. In addition, a time-varying system optimum (SO) toll and a flat ridesharing price are derived to support a stable equilibrium with minimum system cost. Combined with congestion pricing, the ridesharing program can attract more participants and have the larger feasible region with positive ridership because the queuing delay is eliminated and thereby the commuters are more tolerant to the inconvenience caused by sharing a ride. As we expected, compared with no-toll equilibrium (NTE), both overall congestion and individual travel cost are further reduced at SO. This study provides policy insights to support the regulation of ridesharing in the morning peak hours. A combined ridesharing pricing scheme and toll scheme is proposed for optimal system performance.

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