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Connecting e-hailing to mass transit platform: Analysis of relative spatial position ☆

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ABSTRACT

This paper analyzes and compares two different relative spatial position (RSP) designs in an integrated e-hailing/fixed-route transit system: a zone-based design that operates e-hailing vehicles within a zone, and a line-based design that operates e-hailing vehicles along a fixed-route transit line and with a stable headway. To conduct a meaningful comparison, the optimal design problems for both systems are formulated using a same analytical framework based on the continuous approximation approach. A comprehensive numerical experiment is performed to compare various cost components corresponding to the optimal designs, and a discrete-event simulation model is developed to validate the analysis. The analytical and simulation results agree with each other well, with a discrepancy in the total system cost less than 5% in most test scenarios. These results also suggest that the line-based system consistently outperforms the zone-based system in terms of both agency and user costs, for all scenarios tested. Compared to the zone-based design, the line-based design features a sparser fixed-route network (resulting in larger stop spacing) but a higher dispatching frequency. It is concluded that the higher efficiency of the line-based design is likely derived from the strategy of operating e-hailing vehicles with a more regular route/headway structure and allowing ride-sharing.

1. Introduction

Technologies are driving an unprecedented wave of innovations in mobility services. Ubiquitous real-time communications and peer-to-peer interaction enabled by mobile computing promise to more effectively match transport supply and demand at low transaction costs, thereby giving rise to numerous new e-hailing services for personal mobility (e.g., Uber,[1] Bridj,[2] SpotHero[3]) and freight delivery (e.g., Postmates,[4] Roadie[5]). In the long run, the rapidly evolving vehicle automation technology may not only enhance profitability and competitiveness of these on-demand services, but also promote the shift from

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[1] The pioneer of the ride-sharing/e-hailing service (see www.uber.com), which has become a very competitive market with several major players such as Lyft and the China-based Didi.

[2] Known as "the Uber of bus transit" (see www.uber.com), it currently operates in Boston, Washington D.C. and the Kansas City. A similar service, called Via (www.via.com), operates in Chicago and New York.

[3] An on-demand parking service that operates in more than 10 US major cities (see http://spothero.com/).

[4] An on-demand express delivery service (see https://postmates.com/).

[5] A crowd-sourcing on-the-way delivery community (see www.roadie.com).

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private car ownership to pay-per-use mobility models (see e.g. Bertoncello and Wee, 2015). It is widely speculated that the future personal travel market may feature *new transit services* offered by companies that operate a large number of driverless cars. Given its keen interest in driverless car technology[6] and recently announced partnership with Toyota Inc. on vehicle leasing,[7] there is little doubt that Uber is positioning itself to compete in the above futuristic scenario, so are the other eager players such as General Motor/Lyft[8] and Apple Inc./Didi (http://www.xiaojukeji.com/).[9]

Despite their strong appeal, the likes of Uber and Bridj still largely rely on the niche market of door-to-door services. To scale up and succeed as a mass transport platform as envisioned above, greater ride consolidation (both temporally and spatially) and tradeoff between efficiency and level-of-service must be considered. Uber's recent partnership with TransLoc[10] represents a timely move to this direction. The idea is to integrate e-hailing services into public transportation networks by using e-hailing as a demand-responsive feeder for existing transit services. *The purpose of this study is to explore and analyze design options for such an integration*. The main question asked here is how a transit operator can best allocate its resources to fixed-route and e-haling services in order to meet demand. It is worth noting that the current line of thinking about integration appears to occur mainly in one direction, where e-hailing services are matched against the operations of fixed-route services. As the proposed TransLoc-Uber partnership puts it, the goal is to provide the users with a "personalized journey that incorporates the optimal combination of walking, transit and Uber". In contrast, the premise of this paper is that a significant improvement in system efficiency can only be gained when the design and operation of both services are tightly coordinated. In essence, this means that the fixed-route services have to be re-designed in light of enhanced accessibility associated with e-hailing.

A crucial design decision, which motivates this study, has to do with the *relative spatial position of e-hailing services*. By relative spatial position (RSP), we mean the way by which e-hailing services are disaggregated in space and matched with relevant components of transit networks. Determining RSP is fundamental because it has to precede many other design decisions such as fixed-route headway and line spacing, as well as the number of e-hailing vehicles. While RSP may be arranged in many different ways, this paper will closely examine two simple RSP designs under idealized conditions for useful insights and design guidelines. The first design, referred to as the *zone-based RSP*, assigns a set of e-hailing vehicles to feed a given transit stop, and operates them to serve passengers within a relatively small zone surrounding the stop. The other design is called *line-based RSP* because it pairs each fixed transit line with e-hailing vehicles, which are dispatched on predetermined headway but are allowed to deviate from the fixed route to accommodate passengers who need a ride between their origin/destination and the closest transit stop. The prototypes of the zone- and line-based RSP designs have been studied respectively by Aldaihani et al. (2004) and Chen and Nie (2016). This work contributes to the literature by presenting a unifying analysis framework based on the continuous approximation approach, which enables the first comparative study of RSP designs. In addition, an agent-based, event-driven simulation platform is developed for both zone- and line-based RSP designs. The platform is then applied to validate analytical results, and to reveal and compare the performance of the two RSP designs under realistic operational conditions not fully captured by the analysis.

The next section reviews the literature of on-demand transit services, most of which precede the era of e-hailing. Section 3 presents the setting of the analysis framework, with all simplifying assumptions. Section 4 gives the formulation of the optimal design problem for both zone-based and line-based systems. The focus is given to the zone-based system because the line-based system is mostly adopted from the literature. In Section 5, numerical experiments are conducted to compare the performance of optimally configured zone-based and line-based systems. Section 6 first describes the details of the simulation platform, and then presents and discusses simulation results. Section 7 concludes the paper with major findings and possible directions for future research.

2. Literature review

E-hailing, like taxi, is a special form of demand-responsive transit (DRT) that has been practiced and studied long before the era of smart phones. The reader is referred to He and Shen (2015), Wang et al. (2016), and Zha et al. (2016) for recent research regarding e-hailing. The apparent lack of efficiency of taxi services had fueled enthusiasm for more advanced forms of DRT such as dial-a-ride transit (DART), which allows ride-sharing and even transferring through pre-arrangement (Wilson et al., 1976; Stein, 1978). At its core DART is a many-to-many pickup and delivery problem with time window, which is a special class of vehicle routing problems (VRP) known to be NP-hard (Cordeau and Laporte, 2003a).

Many had attempted to tackle the computational challenges associated with DART (e.g. Psaraftis, 1980; Cordeau and Laporte, 2003b; Cordeau, 2006; Melachrinoudis et al., 2007; Ropke and Cordeau, 2009). Yet, the success of real DART systems is often limited by how fast a practically satisfactory solution to a combinatorial problem can be obtained and properly implemented in real time. Black (1995) found many DART systems in operation suffer from high per-capita operating cost

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[6] http://www.govtech.com/fs/perspectives/Ubers-Plan-for-Self-Driving-Cars-Bigger-Than-Its-Taxi-Disruption.html.

[7] http://www.wsj.com/articles/toyota-and-uber-reach-investment-lease-partnership-1464122403.

[8] http://techcrunch.com/2016/03/14/lyft-gm-express-drive/.

[9] http://www.reuters.com/article/us-apple-china-idUSKCN0Y404W.

[10] http://transloc.com/transloc-and-uber-partner-to-pioneer-a-new-standard-in-public-transit.