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Integrating shared autonomous vehicle in public transportation system: A supply-side simulation of the first-mile service in Singapore

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ABSTRACT

This paper proposes and simulates an integrated autonomous vehicle (AV) and public transportation (PT) system. After discussing the attributes of and the interaction among the prospective stakeholders in the system, we identify opportunities for synergy between AVs and the PT system based on Singapore's organizational structure and demand characteristics. Envisioning an integrated system in the context of the first-mile problem during morning peak hours, we propose to preserve high demand bus routes while repurposing low-demand bus routes and using shared AVs as an alternative. An agent-based supply-side simulation is built to assess the performance of the proposed service in fifty-two scenarios with different fleet sizes and ridesharing preferences. Under a set of assumptions on AV operation costs and dispatching algorithms, the results show that the integrated system has the potential of enhancing service quality, occupying fewer road resources, being financially sustainable, and utilizing bus services more efficiently.

1. Introduction

Autonomous vehicles (AVs) are poised to represent a revolutionary future for urban mobility (Silberg and Wallace, 2012). Recent literature on the potential operation of AVs primarily regards them as an upgrade to conventional personal vehicles with the essential characteristics of demand responsiveness, fleet repositioning, and shareability (Alonso-Mora et al., 2017; Correia and van Arem, 2016; Fagnant et al., 2015; Fagnant and Kockelman, 2014). However, if we merely deploy AVs as upgraded versions of human-driven vehicles, we may not derive the optimal benefits of the new technology, especially in large metropolitan areas with high population densities and limited road resources. In cities where public transportation (PT) plays a critical role, the relationship between AVs and the PT system should not be ignored. Most studies, however, do not take into account such relationships. Only a few offer limited insight into the AV-PT interaction and the PT is mostly pitted as a competitor (Chen and Kockelman, 2016 and Mendes et al., 2017). Discussions regarding AV and PT as complementary and integrated are scarce. Liang et al. (2016) compared the service offered by automated taxi systems with those provided by human-driven taxis over the last mile to train service; however, improvements in the PT performance was not the focus of the study. Vakayil et al. (2017) explored a hybrid transit system with on-demand AVs as an additional service to improve metro connectivity; nevertheless, the relationship between AV and bus networks was neglected. Lenz and Fraedrich (2016) discussed, however conceptually, the possibilities of hybridizing AVs with PT, including improvements in inter-

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modality and individualization of the transit service.

To fill the research gap, we examine the attributes of and the interaction among the prospective players in an integrated system (AV operators, PT operators, riders, public authorities, and automakers) and explore the opportunities that AVs can provide when integrated into PT systems. We envision a scenario in which AVs provide a complementary on-demand service to conventional fixed-schedule fixed-route buses for the first/last mile and assess whether the new integrated service improves the performance of the overall system. This study is based on empirical travel demand and transit operation details derived from the smart card data in Singapore.

The remainder of this paper is organized as follows. Section 2 discusses the integrated AV and PT framework and highlights a list of characteristics of AVs that distinguishes the new system from the traditional hybrid public transit system. Section 3 presents the case of Singapore. After analyzing the current PT travel demand focusing on the first-/last-mile trips, we propose a design where we preserve the high demand bus routes, repurpose low-demand bus routes introduce AVs service. Next, we describe the agent-based model and simulate 52 integrated AV and PT scenarios for first-mile trips during morning peak hours. We also simulate the status quo bus operations as the benchmark, again which we evaluate whether the integrated AV-PT system is well-suited to improve the quality of service, occupy fewer road resources, and be financially sustainable, and utilize buses more efficiently. Section 4 concludes this paper.

2. Toward a framework for integrated AV and PT system

There have been decades of efforts to design and to operate an integrated PT system with on-demand flexibly-routed service since Daganzo (1978) and Wilson and Hendrickson (1980). Taking advantages of both operating styles—fixed-route fixed-schedule service for corridors of high demand and density, and demand-responsive service for areas with low ridership, low density and scattered demand (Adebisi and Hurdle, 1982; Chang and Schonfeld, 1991a), several integrated PT systems have been proposed (Aldaihani et al., 2004; Chang and Schonfeld, 1991b; Li and Quadrifoglio, 2009). Various conceptual models evaluating the fixed-route and demand-responsive transit services have also been presented (Diana et al., 2009; Li and Quadrifoglio, 2010; Qiu et al., 2015). Constrained by the 20th-century technology, the integrated demand-responsive transit system faced critical challenges including high costs to operate the service, difficulties to communicate with the riders and manage shared rides, and problems to control drivers.

In recent years, the rapid development of Information and Communication Technology (ICT) has led to the emergence of transportation network companies (TNCs), e.g., Uber and Lyft, and revived interest in flexible on-demand systems. Online communication platforms manage shared rides more efficiently by matching the real-time demand with dynamic fleet operation strategies with lower price for the rides. Some operators have incorporated non-dedicated vehicles into their service models to reduce capital costs, allowing the fleet size to vary dynamically according to changes in demand (see the case of FlexDenmark).

When AVs become available, they may offer an opportunity to address many organizational and technological challenges in the current system such as reducing labor cost, improving compliance with planning and operation control, expanding service hours, avoiding erroneous human-driving behavior, and optimizing the spatial and temporal allocation of the PT services. Fig. 1 summarizes the AV characteristics from the perspectives of operation (AV operator and PT operator), governance (public authority), technology (AV producer), and consumption (AV riders and PT riders), distinguishing the integrated AV-PT system from the traditional hybrid transit system. In this study, we focus on the relationships between AV operators and PT authority, and between AV operators and conventional transit operators. The rest, despite its importance, is beyond the scope of this paper.

The AV operators offer a new travel option from the passengers' point of view. Indicators of conventional PT service quality also apply to the shared-AV service on demand (See the comprehensive set of service indicators in Eboli and Mazzulla, 2011). AV service can be more attractive if the system is able to provide a flexible door-to-door service, cheaper thanks to lowering operating cost, and personalized to fit individual preferences and circumstances. The service can also benefit the elderly or passengers with disabilities. There can also be drawbacks associated with the AV service. The impact on the driver employment will have profound implication on the labor relation, contracting, and social justice in general, which is part of the broad discussion on the social impact of the automation. Without the appearance of human drivers, the driverlessness may raise concerns from riders regarding safety (the maturing of driverless technology), security (preventing crimes in the vehicle) and the quality of customer service in general (e.g., human assistance). These concerns are partially demonstrated in Dong et al. (2017).

AV brings the attention of public authority to understanding the role and impacts of AVs on the mobility system. A variety of organizational structures can be imagined with respect to the ownership of the transit and AV operators, the interaction between the operators, and the degree of regulation and intervention from the public authority. Possible organizational models of the integrated AV and PT systems can be envisioned based on the existing transit governance literature (Bruun, 2013; Costa, 1996; van de Velde, 1999; Wilson, 1991) and the emerging experience in regulating the TNC firms in London, Singapore, and Boston. They include but are not limited to (1) the *laisse-faire* structure; (2) the experience on regulating TNC firms (e.g. in London); (3) the "on-demand para-transit pilot program" led by the Massachusetts Bay Transportation Authority (MBTA); (4) the deregulation of PT in the UK (Wilson, 1991); (5) the "Scandinavian" model (Costa, 1996; van de Velde, 1999); (6) the fully coordinated model. Appendix A summarizes the key characteristics of the six models but does not get into the details of the specific responsibilities and functions of the public authorities and other stakeholders. For instance, within the Scandinavian model, the organizational structures in Copenhagen (Denmark), Malmö (Sweden), and Adelaide (Australia) can be distinguished further based on the level of central planning and the design of incentives to tendering parties (van de Velde, 1999).