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 paratransit 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).
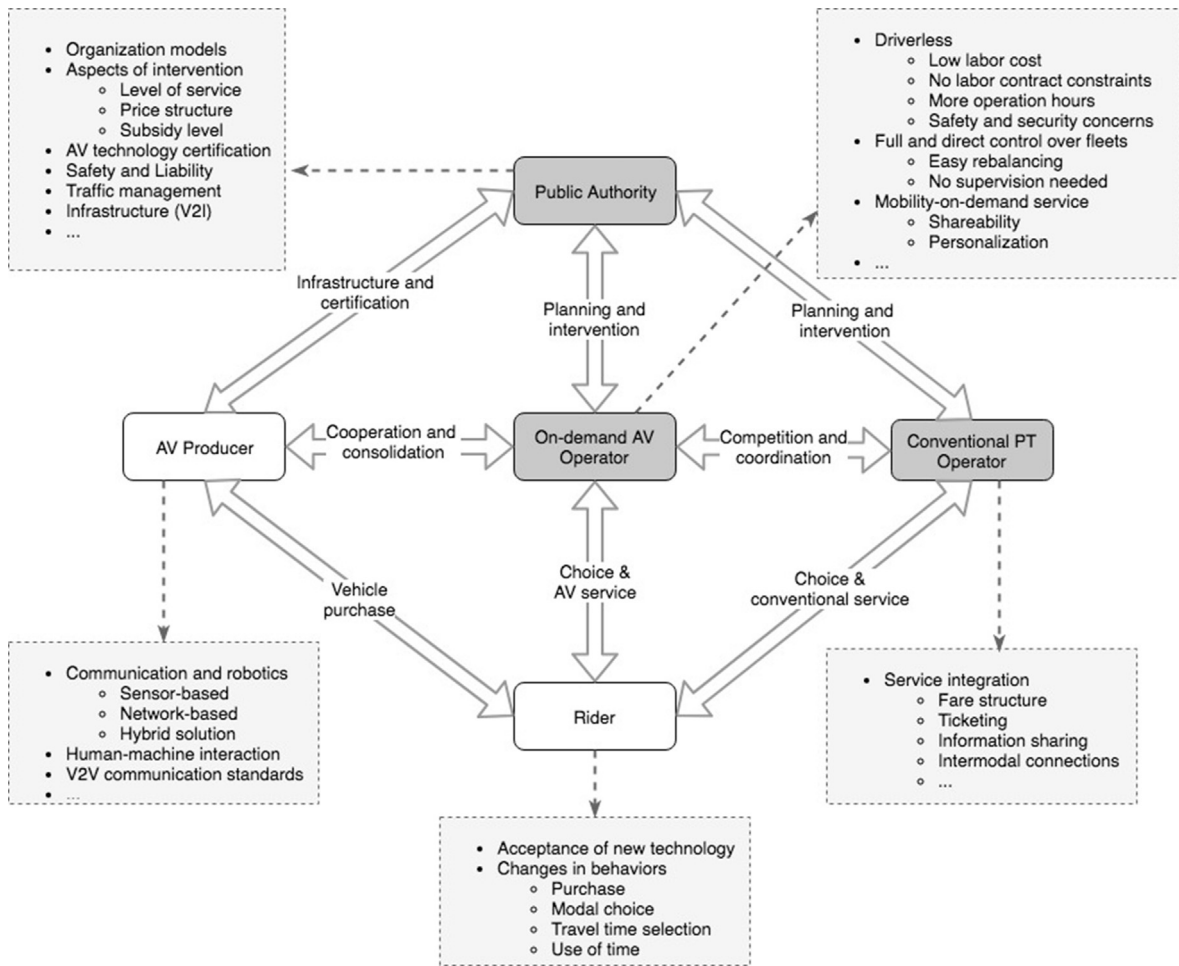
Fig. 1. Stakeholders around AV-PT operation and AV characteristics from the perspectives of operation, governance, technology, and consumption.

2.1. Assumptions of the AV-PT systems based on the organizational models in Singapore

Public transit in Singapore is highly regulated by the Land Transport Authority (LTA), which is responsible for service integration including fares, information, and route design.[1] The subway system, known as mass rapid transit (MRT), is planned and constructed by the LTA, who then leases the operating licenses to transit operators. The LTA tenders out bus services with a contract for five years plus a two-year extension based on service performance. The bus operators compete for the market to win the contract to enter the market, while the bus routes are still designed by the LTA.

Based on the characteristics and regulatory structure of the transport system in Singapore, we identify the opportunity for synergy between AV and PT system and assume the following characteristics of the integrated AV-PT system.

- *Planning and regulation*: the public authority LTA remains responsible for transit network planning and the assignment of service areas and routes.
  o On-demand AV operation is supported and regulated by the public authority.
  o On-demand AV operation is provided in dedicated service areas and is limited to first- and last-mile service in the current phase.
- *Transit fare and subsidy*: The transit fare is heavily regulated. The fare adjustment formula is regularly reviewed to ensure that the fares are in line with the cost structure and productivity achieved in the industry and that they are affordable to the public.
  o The fare structure of the AV service is considered part of the transit fare review and adjustment.
  o The cost for an AV ride is calculated in Section 3 to test the financial viability of the AV service.
- *Coordination and competition*: the current transit system in Singapore is a coordinated system with the unified fare and information structure.
  o AV operation is coordinated with the MRT system for feeder service. In the designated area, the AV operation and the adjusted

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[1] TransitLink, the subsidiary of LTA, is in charge of the specific development of service integration and design.

bus operation are also coordinated (see Section 3 for the specific design).
- *Fare, Ticketing and Information Integration*: the AV service is integrated into the transit system regarding:
  - o Ticketing: the transit smart card (or any other payment systems used by PT) can be used for the AV service.
  - o Fare: the cost of a shared-AV ride is set to be close to the current transit fare.
  - o Information: the operating characteristics of both AV and conventional PT modes are known to each other and available to the passengers.

3. An integrated AV-PT system for the first-mile service in Singapore

First, we examine the first-mile performance in the status quo PT system using the travel records from the contactless e-purse application (CEPAS) card—the transit smart card in Singapore. Second, based on the organizational structure assumed in Section 2, we propose one feasible operational scenario of integrating AVs into the PT system, aiming at improving the first-mile service during the a.m. peak. Finally, we assess the performance of the newly integrated system via agent-based simulation and compare it with the current PT-only system.

3.1. Study area and data

We define the first-/last-mile trips in Singapore as the connecting trips to/from the MRT stations, including walk and bus as the dominant modes. The CEPAS data used in this study covers all PT trips in August 2013, with over 175 million travel records. Since the CEPAS requires the tap-in and tap-out policy in both bus and MRT systems, each trip record archives the date and time of every entry and exit activity and the boarding and alighting stops/stations. The fare policy recognizes the temporally adjacent journey stages as one single journey, which may contain a series of MRT and/or bus rides.[2] The details on the bus trips made before and after the MRT ride are clearly identified.

Appendix B discusses the first-/last-mile travel demand during the entire workdays, and we focus here on the two-hour morning peak (7:00–9:00 a.m.). Fig. 2 shows the volume of passengers entering each MRT station during the morning peak and the mode shares by bus vs. other modes. We highlight four stations with over 10,000 passengers and more than 50% of bus mode share, among which, the Tampines area is chosen as the case study. Tampines has one of the highest population densities in Singapore, with about 240,000 residents living in a 12 km² area (HDB, 2015). The MRT travel demand in Tampines station is also one of the highest: between 7 and 9 a.m. on a typical workday, more than 15,000 passengers use the MRT service, including over 8000 taking a bus to access the train station. Fig. 3 ranks the 27 bus routes (and directions) serving the MRT station by the average workday peak-hour bus ridership. There is an obvious imbalance of patronage: the top five routes account for more than 55% of the first-mile travel demand, and the bottom 11 routes account for less than 10% of the demand. The footprints of the high-demand and low-demand bus routes are illustrated in Fig. B in Appendix C.

3.2. Design and assessment of the integrated AV-PT system

People in Singapore are highly dependent on the MRT system. The first-/last-mile connectivity is one of the major issues in the current system of Singapore. Numerous solutions have been designed and proposed (Lesh, 2013) to improve the connectivity: (1) by proactive planning, such as enhancing walkability (Cervero, 2007), encouraging park-and-ride (Hamer, 2010), and increasing intermodal coordination (Chien and Schonfeld, 1998; Sørensen and Longva, 2011); and (2) by innovative travel modes, such as bike sharing (Cervero et al., 2013; DeMaio, 2009; Shaheen et al., 2010), and electric scooters (Shaheen and Finson, 2003).

We propose an integrated AV-PT system by preserving the high demand bus routes and repurposing low-demand bus routes while using the shared AV service on demand as an alternative:

- The 16 busiest bus routes (shown in Fig. 3) are kept to ensure that 90% of the travel demand is served efficiently.
- The 11 low-demand routes are repurposed in four different ways depending on the specific configuration of the routes: (1) rerouting to reduce the detour, (2) rerouting to bypass the high traffic center, (3) maintaining the route but with larger stop spacing, and (4) shifting the destination to the nearby Simei MRT station. The details of these repurposing options are discussed in Appendix C.
- Only the remaining 10% of the demand previously serviced by the 11 low-demand buses is to be served by the on-demand AV service.

We further assume the following additional AV operation features in the simulation:
On vehicle ownership and operation:

- *Vehicle ownership*: individually owned AVs are not taken into account in the model; and the fleet-based AVs are rented from non-dedicated vehicle providers (e.g., car-rental companies) whenever needed.
- *Labor cost:* there is no cost for human drivers. Service and maintenance cost of AVs are accounted in the rental fees paid to the car

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[2] According to the LTA, in a single journey, the transfer time should be less than 45 min while the total travel time should be less than two hours.
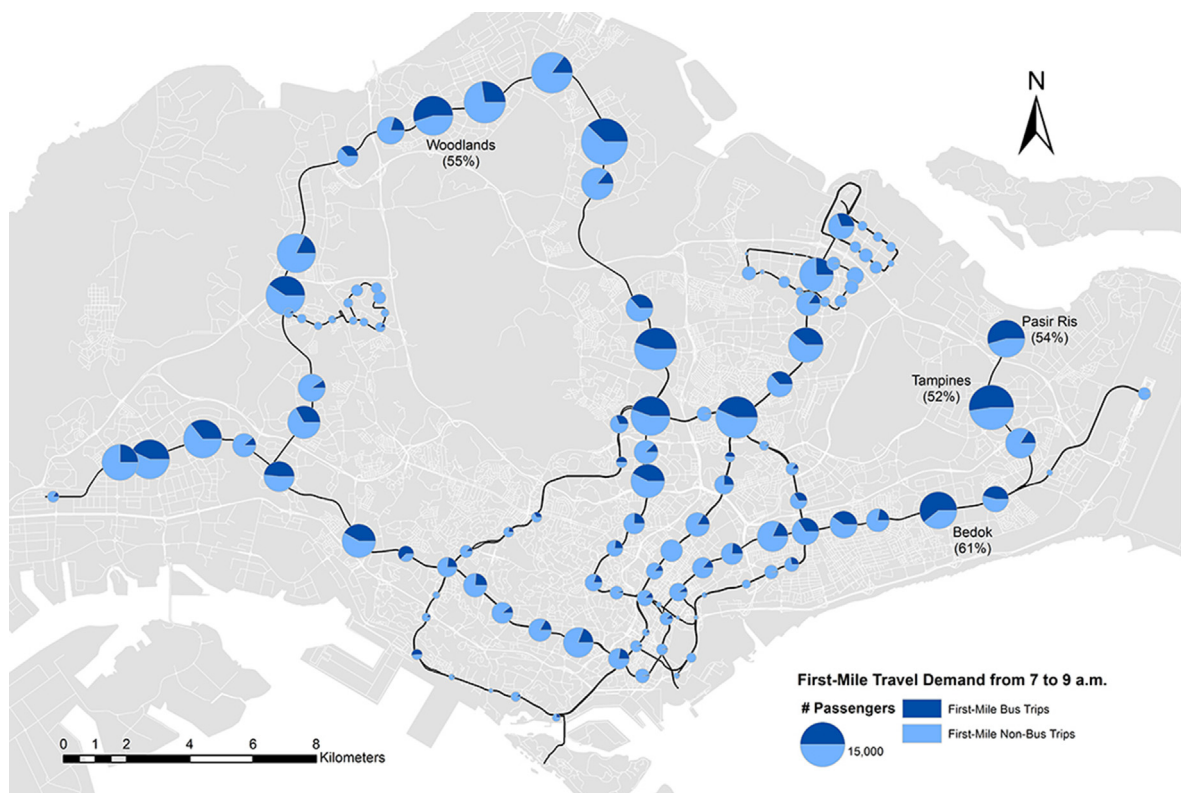
Fig. 2. First-mile travel demand between 7 and 9 a.m. (Calculated by the authors based on CEPAS smart card data).
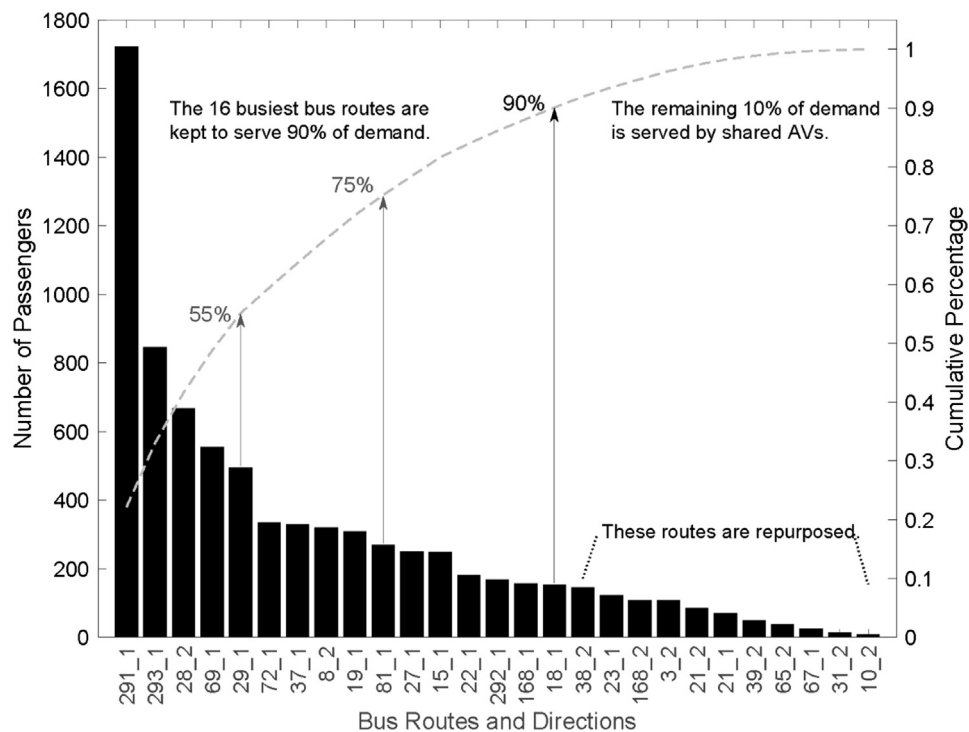

Fig. 3. Bus ridership to Tampines MRT by route. (Calculated by the authors based on CEPAS smart card data; "_1" and "_2" indicate the two directions of the same bus route).
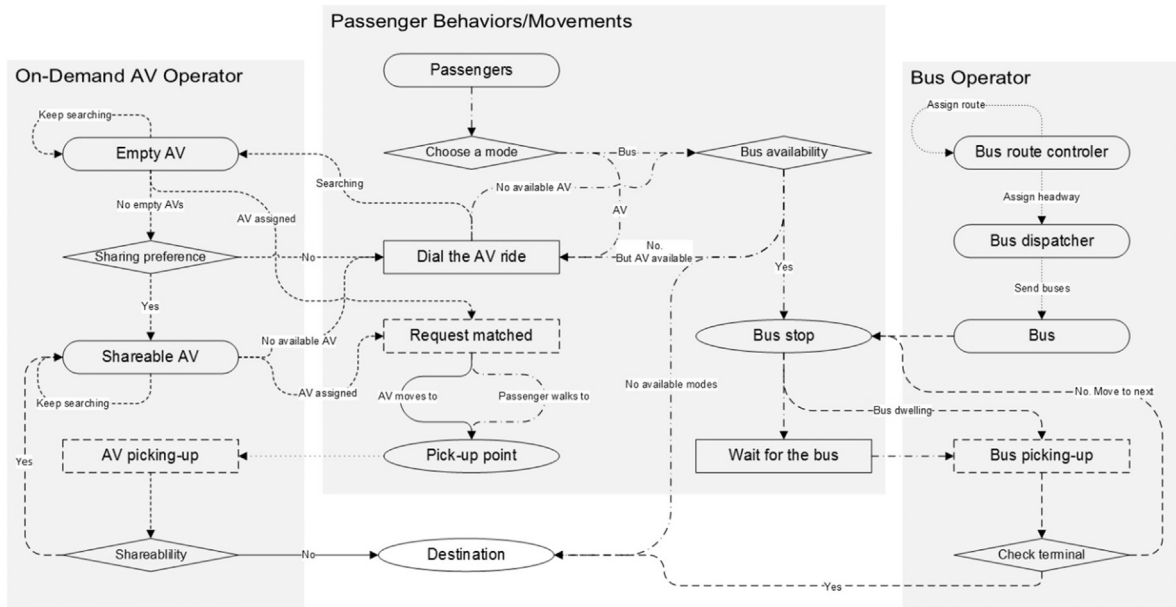
Fig. 4. Agent-based simulation of passengers, buses and AVs (rounded rectangles refer to the agents, ellipses refer to locations, rectangles with solid line refer to the movements of agents, rectangles with dashed line refer to the interaction between agents, and diamonds refer to the decisions of agents).

rental companies.

- *Operation Compliance:* the AVs comply fully with the central controller and do not reject service qualifying requests from customers.
- *Fleet rebalancing*: when the AV is idle, it is sent to a parking area.[3]

On communication and sharing:

- *Mobility-on-demand:* the AV service is requested on demand.
- *Real-time shareability*: The requests for ridesharing are processed and responded to in real-time. Both the sharing and no-sharing scenarios are simulated and compared.

We built an agent-based model,[4] simulating the behaviors and interaction among three types of agents in the system: the passenger, the AV, and the bus, shown in Fig. 4.

3.2.1. Passenger behaviors

This model focuses on the passengers who used to ride the bus to the MRT station. The incidence of passenger trips based on the bus boarding in every 15 min during the peak hours. A Voronoi diagram based on the location of bus stops is generated to assign travel demand to each building.[5]

As AVs are not yet widely available to the public, current worldwide studies on AV preference are hypothetical (e.g., Bansal et al., 2016; Krueger et al., 2016; Kyriakidis et al., 2015; Lu et al., 2017; Payre et al., 2014; Shin et al., 2015; Yap et al., 2016) and the settings in the cases from other countries may not transfer easily to the context of Singapore. Since the consumer preference for AVs in Singapore is not the focus of this study, this paper does not model the mode choice behavior. Instead the model assumes the fixed modal split between bus (90%) and AV (10%) and focuses on the supply-side simulation. But it is a critical future research area to have a dedicated AV preference study based on the local context in Singapore.

When the AV is chosen as the travel mode, the passengers start to call for the ride repeatedly until the system has successfully booked a car for him/her. Once the vehicle is assigned, he/she then moves to the pick-up location to wait for the AV. As the density of bus stops in Singapore is very high, the pick-up location is set as the closest bus stop from the passenger. To prevent a passenger from

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[3] We do not introduce more sophisticated anticipatory rebalancing algorithms in this paper, but they can be incorporated in the future research. See Wen et al. (2017). In the simulation vehicles simply return to the parking lot of the Tampines MRT station, owned by public authority for both bus and shared AV parking. The parking cost is thus not included in the model.

[4] Both the analytical approaches and simulation approaches can be used to assess an integrated AV-PT system. Analytical approaches are important, but the closed form solution may not be available in the context of the dynamic and complex real world. They are often based on a hypothetical and small transit network (e.g., Aldaihani et al., 2004; Li and Quadrifoglio, 2009).

[5] Due to the lack of demographic information at the building level, the population are assumed to be evenly distributed to the buildings in the cell.

waiting forever when no AV is available, a maximum waiting time is set to 10 min in the study, beyond which he/she will forgo the AV request and travel by bus.

When the bus is chosen, the passenger will walk directly to the bus stop to wait for the next bus. As the frequency of bus service is high (less than 10 min headway), the model assumes that passenger arrival time is independent to the bus schedule (Abkowitz and Tozzi, 1987; Fan and Machemehl, 2002; Frumin and Zhao, 2012). Thanks to the high service reliability of Singapore's bus system, all passengers get onto a bus within 10 min waiting time.

3.2.2. On-demand shared AV service

The concept of the mobility-on-demand system was proposed and demonstrated in the 1970s, and was called Dial-a-Ride Transit (DART) (Wilson et al., 1976). Two decades later, Dial (1995) proposed a fully automated DART system. More advanced transit systems integrating various vehicle sharing services—including buses and taxis—were recently designed and tested (e.g., Atasoy et al., 2015; Djavadian and Chow, 2016; Jung and Jayakrishnan, 2016). In this study, the on-demand AV service with ridesharing resembles a taxi-sharing system (Galland et al., 2014; Martínez et al., 2015) but the service area is restricted to the Tampines town with only the first/last mile service, consistent with the proposed usage of the AV prototype in Singapore (Chong et al., 2011). The driving behaviors for all AVs are identical, and no booking requests are rejected. The idle AVs are sent to the parking lot of the Tampines MRT station if there is no demand for AV. Each AV allows a maximum of four passengers, the capacity of the AV prototype, to share the ride. As discussed in Section 2.1, the AV operation is regulated by the transit authority to be complementary to the bus. It does not compete against bus service for a bigger market share.

The AV routing follows the shortest path. We assumed that a passenger prefers to ride alone if possible even when he/she agrees to share the ride. Thus, when a passenger calls for a ride, the system first scans all empty AVs. If there are empty AVs, the system assigns the closest available AV to pick up the passenger. Once the AV and the passenger are matched, a notice is sent to the passenger requesting a meet-up at the pick-up point. If there are no empty AVs, the system searches for all occupied AVs, the passengers of which have agreed to share the ride, based on pre-assigned passenger sharing preference. The criteria to match the shared rides are as follows. For each shareable AV, after picking up the passenger at location i, the decision of whether to pick up the next passenger at location j is determined by the following conditions:

- The vehicle must have enough available seats.
- *Global detour constraint:* For a passenger at location i in a shared trip, regardless of the number of passengers in the AV, and regardless of the boarding order of passenger i, the total travel time from pick-up location of passenger i to MRT station s, T_{is}, must be less than the direct service time, t_{is} multiplied by an overall detour ratio, α:

$$T_{is} < \alpha \cdot t_{is}, \text{ where } \alpha > 1. \tag{1}$$

- *Incremental detour constraint:* In each event of picking up an additional passenger at location j, the deviated travel time for the previous passenger i due to picking up j (i.e., $t_{ij} + t_{js}$) must be less than the direct service time, t_{is}, multiplied by the step-by-step detour threshold, β.

$$t_{ij} + t_{js} < \beta \cdot t_{is}, \quad \text{where } \beta > 1. \tag{2}$$

The pricing structure is purely distance-based, without a "base fare". It also reflects the detour ratio of each passenger. For ridesharing trips, a discount for passenger i is calculated based on the actual detour ratio r. The discounted price, P_i is computed as in Eq. (3).

$$P_i = p \cdot d_i \cdot (1 - r^\gamma) \tag{3}$$

where

- p is the base AV fare per km;
- d_i is the direct travel distance of passenger i in km;
- D_i is the detoured actual distance;
- $r = \frac{D_i}{d_i} - 1$, the detour ratio;
- γ is the degree of discount offered due to the detour.

In the simulation, we set p_i to S\$1 per kilometer which is at the same order of magnitude as the base bus fare during peak hours,[6] α to 2, β to 1.2, and γ to 2. Please note that past literature shows that given the bus pricing structure in Singapore, there is no price variation in the first mile access by bus (Mo et al., 2018). We cannot find locally relevant willingness-to-pay estimates from prior literature. Thus, we design the pricing discount and the distance detour to roughly balance each other so that the fixed demand assumption remains reasonable.

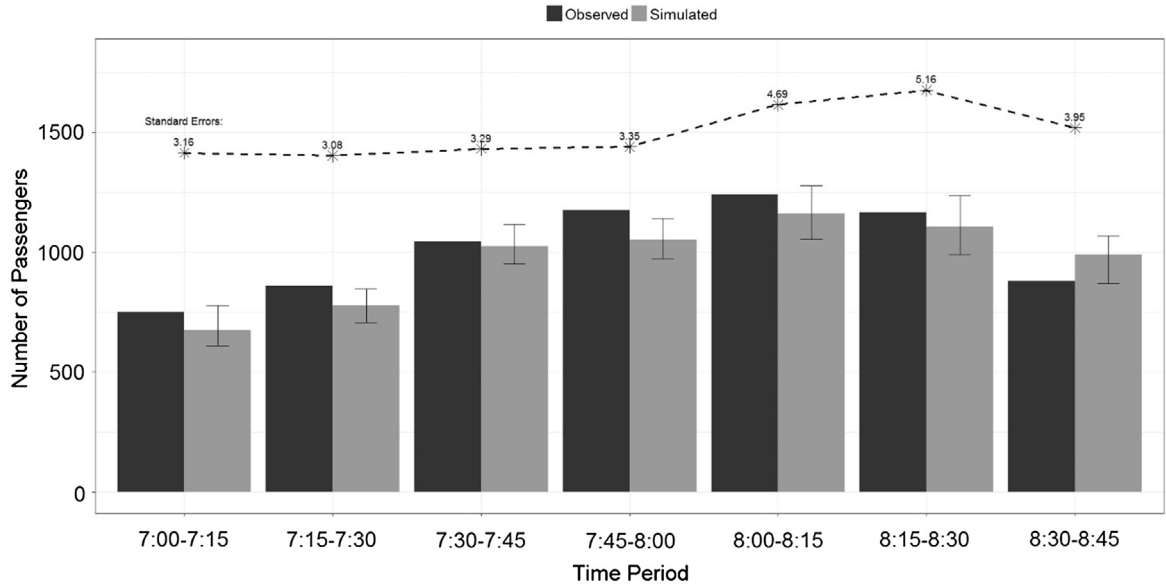[6] The base bus fare is about 0.87 Singapore dollar.

Fig. 5. Number of boardings comparison between simulation and CEPAS data.

3.2.3. Bus routing and dispatching

While the shared-AV service is on-demand, the bus service still operates on a fixed route and fixed schedule basis. Two agents are introduced for bus routing and dispatching. The bus route controller is a high-level agent that manages all bus routes, including the stop sequences to follow and the headways of each bus route during different time periods. We assigned a bus dispatcher for each bus route. Based on the stop lists and headways, the bus dispatchers generate buses for the corresponding routes according to the actual bus schedule. The data for bus routes and schedules are provided by the LTA. The routes used are the ones presented in Fig. 3, which intersect the Tampines area and stop at the MRT station.

Once a bus is generated by the dispatcher, the route is determined based on a sequential stop list. The bus vehicle follows the route at a constant speed. Upon arrival at a bus stop, each bus agent dwells for a certain amount of time to pick up all the passengers who are waiting at the bus stop at the bus arrival time. The actual bus dwell time depends on the number of passengers entering and exiting the bus, as well as the total number of passengers on the bus. However, we simplify the dwell time to be fixed (30s) in the simulation due to the lack of detailed operational information and corresponding coefficients. The waiting time of each passenger is archived, and the number of passengers onboard is logged. We also calculate the travel time and travel kilometers for each passenger.

The model was coded in AnyLogic 7.3. We executed the simulation between 6:00 and 9:00 a.m. (10,800 s) where one second in the simulation corresponds to one second in reality. The first hour (6–7 a.m.) was regarded as the warm-up period; the outputs from the last two hours (7–9 a.m.) were recorded and analyzed.

3.3. Simulation results and analysis

3.3.1. Benchmark scenario: Bus-only service

We first simulated the status quo scenario with only the bus services, following the existing bus routes, and used it as the benchmark to compare the new integrated AV-PT scenarios. The simulation was run for 100 iterations. Fig. 5 compares the observed numbers of boardings in the CEPAS data with the simulated numbers in the benchmark model in every 15 min interval. For most time intervals, the range of the simulated results captures the empirical values.

We also compared the share of ridership in each bus route between the simulated results and the observation using the root-mean-square error (RMSE):

$$\text{RMSE} = \sqrt{\frac{\sum_{n=1}^{N} \sum_{r=1}^{R} (\hat{\rho}_{nr} - \rho_{nr})^2}{N \cdot R}},$$

(4)

where $\hat{\rho}_{nr}$ is the simulated share of ridership of the bus route r at the n-th simulation; ρ_{nr} is the observed share of ridership of bus route r at the n-th simulation; N is the total number of simulation runs; R is the total number of bus routes. The RMSE was 0.026, indicating that the simulated demand in each bus route well fitted the actual patronage derived from the CEPAS data.[7]

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[7] The visual comparison in Fig. 5 and the RMSE are both aggregate measures, which do not capture the variations in the number of passenger boardings at the bus stop level, resulting in an overestimation of the realism of simulation.
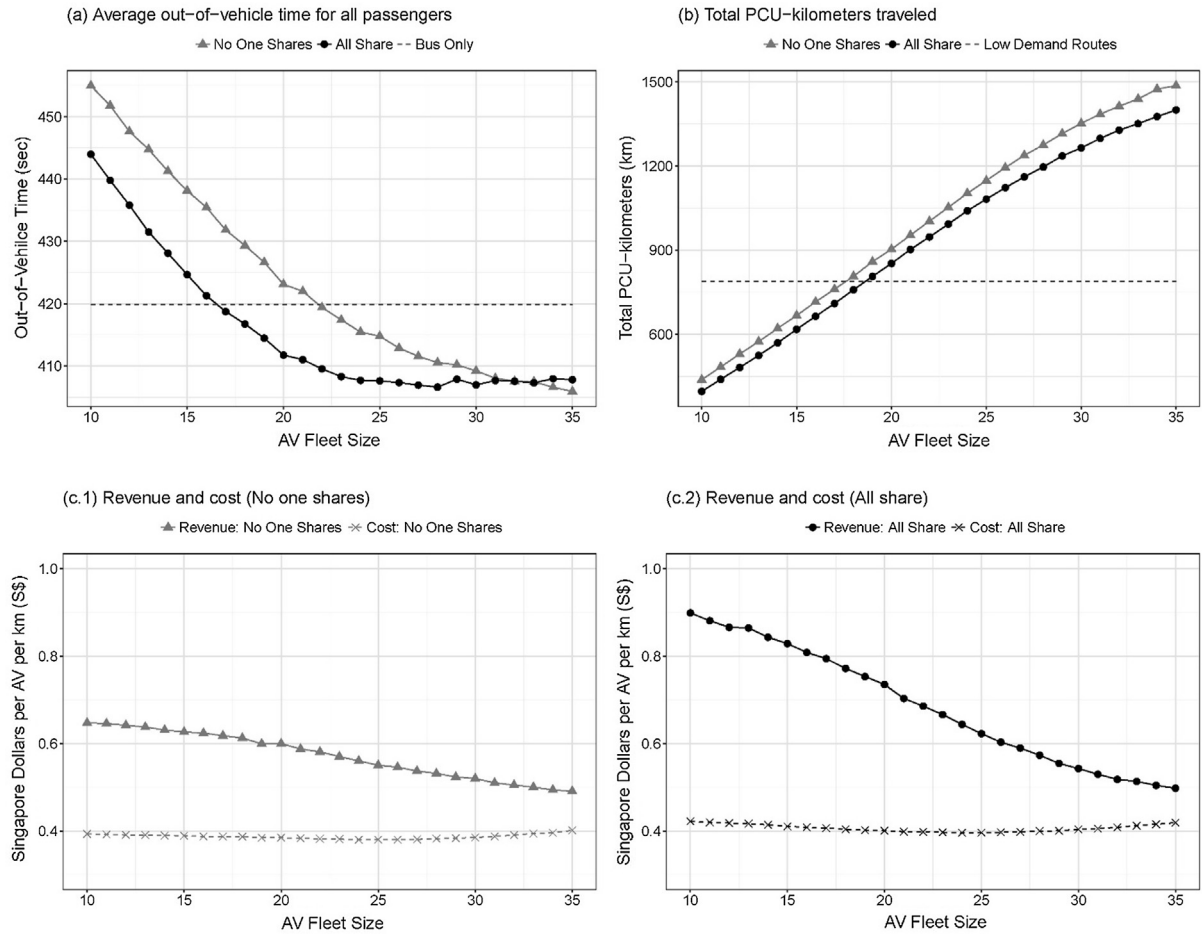
Fig. 6. Simulation results.

3.3.2. Integrated AV-PT scenarios

As proposed in Section 3.2, we simulated the scenarios where shared AVs would accommodate the first-mile service as a re-placement of the 11 low-demand bus routes. 90% of the passengers would still choose the bus, as per usual, whereas the remaining 10% would hail an AV for the ride to the MRT station. After repurposing the 11 bus routes, we evaluated the service performance of different AV fleet sizes (from 10 to 35 vehicles) and with two extreme settings of sharing preference of the AV riders: (1) no one is willing to share the ride, and (2) everyone is willing to share. A total of 52 AV-PT scenarios were developed, and for each scenario, 100 times of simulations were run.

Among the many factors affecting system performance, we look into three perspectives to evaluate the integrated AV-PT system:

- Passenger perspective (i.e., service quality): travel time, particularly the out-of-vehicle travel times (OVT) including walking time and waiting time
- System perspective (i.e., road traffic): we use the passenger car unit kilometers (PCU-km) as the approximation to the road resource usage for mixed-vehicle fleets (BITRE, 2015; BTRE, 2007). The PCU-km is derived as the product of the vehicle-kilo-meters traveled and the passenger car equivalent (PCE) factor. The empirical PCE factor for buses in Singapore is approximately 2.75 (Fan, 1990; Yeung et al., 2015). As the AV is classified as a personal car, its PCE factor is one.
- Business perspective (i.e., operating cost and revenue): whether the AV service can be financially viable based on the proposed pricing model.

The simulation results of the 52 scenarios are plotted in Fig. 6, where each dot represents the average value of 100 simulation runs; the triangles represent the non-ridesharing setting, whereas the circles represent the all-ridesharing setting. The dashed line shows the average value of 100 simulation runs of the bus-only benchmark scenario.

Owing to the heat and humidity in Singapore, the outdoor walking time and the waiting time are of high importance to service quality. The average OVT in the benchmark bus-only scenario is approximately 420 s. We recorded in the simulation the total time spent by each passenger from his/her incidence being generated to the time when he/she boards a bus or AV. Fig. 6(a) compares the

average OVT of all passengers in the AV-PT scenarios with that in the benchmark bus-only scenario. More AVs reduce the OVT until they saturate; and the OVT is shorter when rides are shared for the AV fleet size less than 30, beyond which sharing no longer affects the OVT. The first-mile travel demand can be served by only 17 AVs with ridesharing for the average OVT to be on par with the benchmark scenario. However, without sharing, we would need 22 AVs, an increase of fleet size by a third, to guarantee the same service quality.

Fig. 6(b) indicates the total PCU-km in different AV-PT scenarios. By repurposing the 11 low-demand bus routes based on the strategies in Appendix C (mostly to reduce detours), we can save a total of 860 PCU-km, which we consider as the acceptable "quota" for AVs in order not to increase the total traffic in the study area. The simulation results indicate that about 18–19 AVs can be accommodated in the study area within the traffic "quota." Since our simulation model only uses the basic heuristic AV dispatching and assignment algorithms, the AV-PT system performance can be further improved with more advanced algorithms.

Fig. 6(c.1) and (c.2) plot the estimated revenue and cost per kilometer for various AV fleet sizes. The operation cost of AVs is based on the car leasing plan between Uber and SMOVE,[8] an emerging car-sharing company in Singapore. We assume that the AVs are owned by SMOVE, or its equivalent, and rented to the AV operators using the same leasing plan: the costs being calculated based on the usage of vehicles in terms of both time and distance. The simulation results show that smaller fleet size has higher profits per kilometer. Sharing increases the profit margin per kilometer. When the fleet size increases, the profit gap between sharing and non-sharing scenarios shrinks. The integrated AV-PT service is financially viable in the tested range of fleet size assuming the above cost structure and the pricing model.

4. Discussion

In addition to the 90%-10% scenario (90% by high demand bus routes and 10% by AV) reported above, we also tested two alternative AV-PT scenarios: the first is an extreme case where all first mile bus services are replaced by the AVs, and the second is to use AV to serve 45% of first-mile bus demand by preserving only the 5 busiest bus routes. Appendix D shows that in both alternative scenarios, the system performance worsens, i.e., there will be far larger PCU-km in the system to maintain the same level of service quality as in the benchmark case. We should not take it for granted that an integrated AV-PT system will automatically improve the status quo. Instead, it requires attentive research and innovative design to identify the opportunity window where an optimal combination of AV and PT can enhance service quality, utilize buses more efficiently, occupy fewer road resources, and be financially sustainable.

The Ministry of Transport (2017) of Singapore is planning for the pilot deployment of AVs in several planning areas. The integration of AV into the PT system is one of the primary objectives, including the exploration of operational characteristics and business models. Our study proposes an integrated AV-PT system based on Singapore's PT organizational structure and demand characteristics. Specifically, we envision a synergic system in the context of the first-mile service during morning peak hours, where high-demand bus routes are preserved, low-demand routes are repurposed, and shared AVs are introduced as an alternative, and evaluate the system from the passenger, business and system perspectives using agent-based simulation.

The real world is a complex nonlinear system. There is a large room to improve the simulation model in future research:

- The 90%-10% scenario is an intuitive design. A more systematic approach to optimize the PT-AV split should be considered.
- The fixed AV demand is a strong assumption. A full multimodal demand model should be developed based on consumer preference surveys conducted in Singapore for the estimation of the mode choice between the bus, AVs and walking in the first-mile access to MRT stations.
- A dynamic interaction between demand (modal choice) and supply (AV and bus fleets) should be taken into consideration (See Wen et al., 2018).
- The dispatching of AV in the current simulation is based on simple heuristics. A more efficient ridesharing model can be incorporated with more sophisticated algorithms to optimize the ridesharing efficiency.
- Other sub-models such as traffic flow models and bus dwelling time models can also be integrated to make the simulation closer to the real-world circumstances.

Finally, the case study presented in the paper is only one of many possible ways to integrate the shared AVs into the PT system from a planning perspective. As in Fig. 1, there are many alternative schemata from the viewpoints of operation, governance, technology, and consumption, e.g., pricing or ticketing integration, information sharing, institutional design, etc. Private companies can also be potential AV fleet owners and operators. Various ownership structures affect the interests and incentives of different players, leading to different behaviors in the integrated mobility system. Each operator may have its own strategies toward its peers, e.g., one may choose to compete against or to coordinate with the others.

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[8] See https://www.smove.sg/#pricing for more details.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tra.2018.04. 004.

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