Semi-on-Demand Transit Feeders with Shared Autonomous Vehicles — Service Design, Simulation, and Analysis

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1 INTRODUCTION

The advent of shared autonomous vehicles (SAVs) offers new avenues to enhance multimodal public transit services, particularly as feeders in less dense areas (Ng *et al.*, 2024a). With lower operating costs, they can address the first-mile-last-mile problem and bring passengers to other transit modes more effectively than conventional ride-sharing. Extensive reviews (Errico *et al.*, 2013, Vansteenwegen *et al.*, 2022) highlight the evolution of on-demand transit systems and the integration of SAVs, whereas the operations are modeled with agent-based simulation (e.g., Alonso-Mora *et al.*, 2017, Fagnant & Kockelman, 2018, Dandl *et al.*, 2021) and Macroscopic Fundamental Diagrams (e.g., Beojone & Geroliminis, 2023).

Semi-on-demand (SoD) hybrid-route services (Fig. 1), investigated by Ng & Mahmassani (2023) and Ng *et al.* (2024b), combine the cost efficiency of fixed-route buses in denser areas with the flexibility of on-demand services in less populated regions, thereby enhancing convenience and attracting more passengers. In a SoD route, SAVs first serve all fixed-route stops based on a schedule, then drop off and pick up passengers in the flexible route portion (pre-determined with length x_f), and return to fixed-route scheduled stops and the terminus.

With the theoretical formulations of costs and benefits derived in the previous works, this study focuses on the service design and simulation of the SoD hybrid-route transit feeders using SAVs. First, we conceptualize the service and determine the schedule and fleet size analytically considering detours, service guarantee, and peak/off-peak service level. Second, we conduct agent-based simulations on ten existing bus routes in Munich, Germany, optimize the flexible route portion x_f and headway h, and examine the benefits of converting these fixed routes to hybrid routes (in terms of access, waiting, and riding times for users and vehicle distances and requirements for operators). Third, by analyzing the simulation results, we identify SoD use cases with respect to demand and service characteristics, contrast theoretical predictions, and study variations in user experience to investigate the equity impacts.

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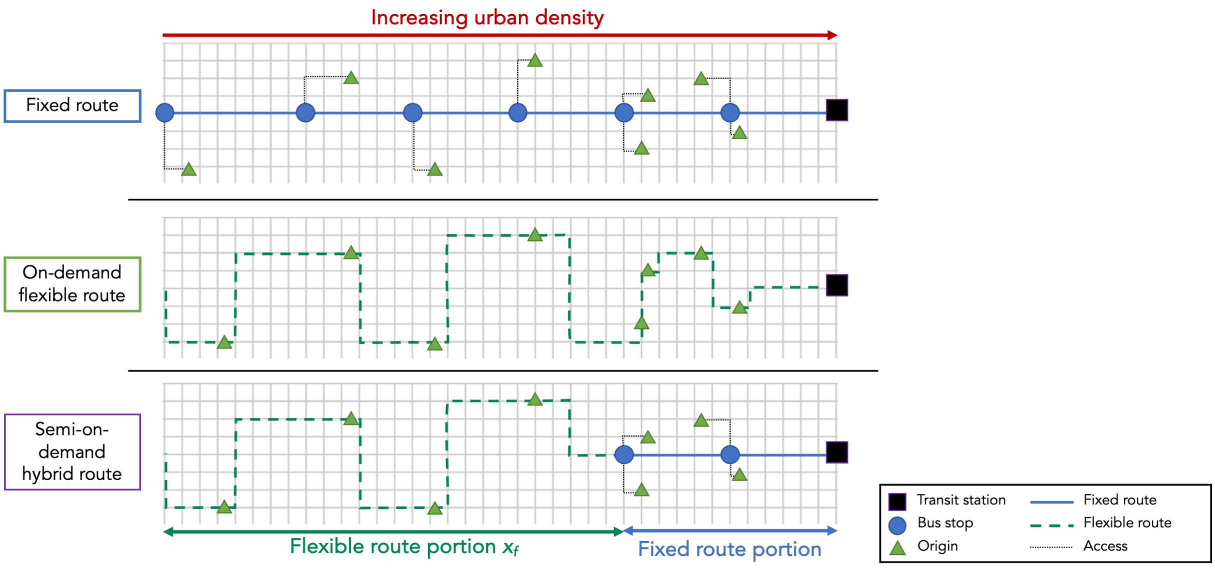

Figure 1 – *Illustration of semi-on-demand hybrid route as a feeder service*

2 METHODOLOGY

2.1 Service Design

The goal of the SoD service design is to minimize total average generalized cost c^G in Eq. (1), factoring in travel times (access t_r^A, waiting t_r^W, and riding t_r^T) and vehicle operating costs (measured by distance d_v and vehicle time t_v^V). A SoD schedule is formed by fixed stops (existing route schedule) and the flexible route portion (existing journey time plus allowable vehicle detour time $t^{(c)}$). Serving a certain level c (say 95%) of stochastic demand requires an adequate $t^{(c)}$. We derive its cumulative distribution function in Eq. (2) with the assumptions of (i) independently uniformly distributed detours for requests ($Y_r \sim \text{Uniform}(0, b)$), (ii) Poisson occurrences of flexible route requests ($N \sim \text{Poisson}(\lambda)$), and (iii) constant vehicle speed v_d. Considering the fleet size of fixed-route services at peak hours (with headway h_p) with round-trip time t_r, we also show the upper bound of $t^{(c)}$ in Eq. (3) deploying the same SAV fleet for SoD services at off-peak hours (with headway h). The two equations are used to design schedules for different lines and yield statistical insights into the trade-offs between service guarantee, performance, and operating costs, supporting subsequent analytical SAV fleet size settings based on demand and cost forecast.

$$c^G = \sum_{r\in\mathcal{R}} (\gamma^A t_r^A + \gamma^W t_r^W + \gamma^T t_r^T) + \sum_{v\in\mathcal{V}} (\gamma_v^O d_v + \gamma_v^V t_v^V) \tag{1}$$

$$P(T \le t^{(c)}) = \sum_{n=0}^{\infty} \frac{e^{-\lambda}\lambda^n}{(n!)^2} \sum_{k=0}^{\lfloor x \rfloor} (-1)^k \binom{n}{k} (x-k)^n, x = \frac{v_d}{2b} t^c \tag{2}$$

$$t^{(c)} \le t_r \left(\frac{h}{h_p} - 1 \right) \tag{3}$$

2.2 Simulation

The simulation (adapted from Engelhardt *et al.*, 2022) models the interaction of customers $r \in \mathcal{R}$, a service operator, and SAVs $v \in \mathcal{V}$ within a predefined network. In discrete time steps, the operator evaluates customer requests (a function of access distance) and assigns them to individual SAVs operating on SoD schedules ψ of fixed and flexible routes, considering constraints, e.g., maximum waiting and travel times and vehicle capacity. Insertion heuristics minimize the objective $\rho(\psi)$ in Eq. (4) to balance vehicle distance $d_{v,\psi}$, travel time $a_{i,\psi} - t_i$, and requests served (overall n_ψ^R and by fixed routes n_ψ^S), while connecting stops with shortest-path routing. Apart from aggregate metrics, this agent-based simulation further enables analysis of variation in individual user experiences and system performances.

$$\rho(\psi) = \sum_{v \in \mathcal{V}} \gamma_v^O d_{v,\psi} + \sum_{r \in \mathcal{R}} \gamma^R (a_{r,\psi} - t_r) - \gamma^R n_\psi^R - \gamma^S n_\psi^S \tag{4}$$

3 RESULTS

We conduct analysis with schedule setting and agent-based simulations on ten existing bus routes in Munich, Germany, illustrated here with results for route 193 at a 5-minute headway (Fig. 2a).

3.1 Schedule setting

The theoretical cumulative distribution of $t^{(c)}$ in Eq. (2) under different x_f is shown in Fig. 2b. Higher service guarantee (e.g., 95% level) requires much longer vehicle detour times, infeasible for longer x_f considering the upper bound in Eq. (3) posed by the fleet size limit (shown in dashes). The theoretical values are close to simulation results (partly shown as crosses for each x_f), with the remaining discrepancy explained by factors such as road layouts.

(a) *Munich bus route 193 and a simulated example of semi-on-demand hybrid route*

(b) *Distributions of $t^{(c)}$ under varying flexible route portions x_f*

Figure 2 – *Example results of simulation and schedule setting*

3.2 Simulation example

With moderate flexible route portions x_f, the more convenient service provided by the flexible routes leads to more requests satisfied without a considerable increase in generalized cost, as a balance between reduced access time and increasing waiting and riding times (Fig. 3, theoretical values in dashes). Its effects on the discrepancy in service experienced by users are shown in Fig. 4, with higher waiting time variances at longer x_f especially at 80% level.

4 DISCUSSION

This study addresses research gaps in SoD service design, simulation, and analysis to evaluate benefits in different transit feeder scenarios in terms of demand and service settings. The allowable detour time estimation enables schedule settings without simulations. The trade-offs between service guarantee, detours, and vehicle requirements, as well as the impacts on fleet size, are demonstrated with more scenarios. The simulation results, in terms of demand satisfied and generalized cost, corroborate the SoD benefits of door-to-door convenience that attracts more passengers without excessive detours and operator costs at moderate flexible route length.

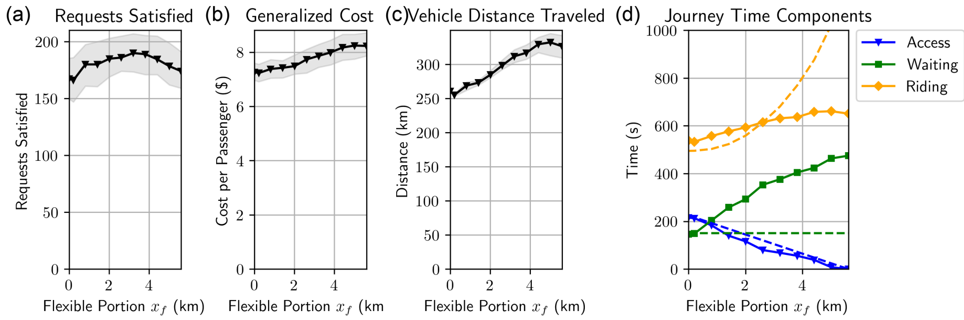

Figure 3 – *Results under varying flexible route portions x_f (95% confidence intervals in shade)*

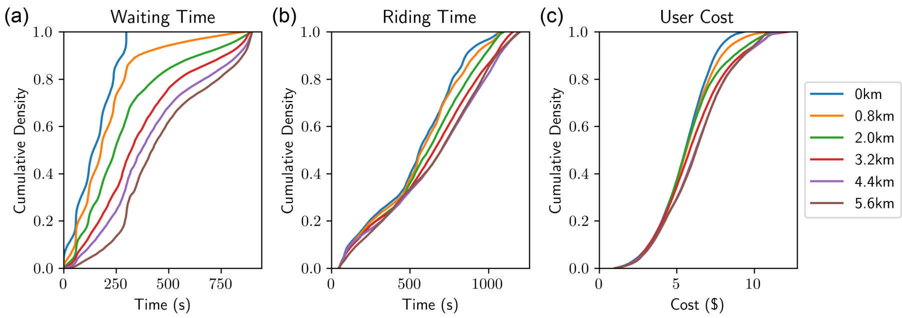

Figure 4 – *Distribution of user experience metrics under varying flexible route portions x_f*

The impacts on user experience are further studied with multiple simulations and different demand settings. A wider range of results, e.g., cross-route comparison, enhances the precision of application scenario delineation of SoD with SAVs to support multimodal transit systems.

References

Alonso-Mora, Javier, Samaranayake, Samitha, Wallar, Alex, Frazzoli, Emilio, & Rus, Daniela. 2017. On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment. *Proceedings of the National Academy of Sciences*, **114**(3), 462–467.

Beojone, Caio Vitor, & Geroliminis, Nikolas. 2023. A dynamic multi-region MFD model for ride-sourcing with ridesplitting. *Transportation Research Part B: Methodological*, **177**, 102821.

Dandl, Florian, Engelhardt, Roman, Hyland, Michael, Tilg, Gabriel, Bogenberger, Klaus, & Mahmassani, Hani S. 2021. Regulating mobility-on-demand services: Tri-level model and Bayesian optimization solution approach. *Transportation Research Part C: Emerging Technologies*, **125**, 103075.

Engelhardt, Roman, Dandl, Florian, Syed, Arslan-Ali, Zhang, Yunfei, Fehn, Fabian, Wolf, Fynn, & Bogenberger, Klaus. 2022. *FleetPy: A Modular Open-Source Simulation Tool for Mobility On-Demand Services.*

Errico, Fausto, Crainic, Teodor Gabriel, Malucelli, Federico, & Nonato, Maddalena. 2013. A survey on planning semi-flexible transit systems: Methodological issues and a unifying framework. *Transportation Research Part C: Emerging Technologies*, **36**, 324–338.

Fagnant, Daniel J., & Kockelman, Kara M. 2018. Dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas. *Transportation*, **45**(1), 143–158.

Ng, Max T. M., & Mahmassani, Hani S. 2023. Autonomous Minibus Service With Semi-on-Demand Routes in Grid Networks. *Transportation Research Record*, **2677**(1), 178–200.

Ng, Max T. M., Mahmassani, Hani S., Verbas, Ömer, Cokyasar, Taner, & Engelhardt, Roman. 2024a. Redesigning large-scale multimodal transit networks with shared autonomous mobility services. *Transportation Research Part C: Emerging Technologies*, Mar., 104575.

Ng, Max T. M., Dandl, Florian, Mahmassani, Hani S., & Bogenberger, Klaus. 2024b. Semi-on-Demand Hybrid Transit Route Design with Shared Autonomous Mobility Services. *In: 103rd Transportation Research Board Annual Meeting.*

Vansteenwegen, Pieter, Melis, Lissa, Aktaş, Dilay, Montenegro, Bryan David Galarza, Sartori Vieira, Fábio, & Sörensen, Kenneth. 2022. A survey on demand-responsive public bus systems. *Transportation Research Part C: Emerging Technologies*, **137**, 103573.