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Dynamic autonomous vehicle fleet operations: Optimization-based strategies to assign AVs to immediate traveler demand requests☆

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ABSTRACT

Motivated by the growth of ridesourcing services and the expected advent of fully-autonomous vehicles (AVs), this paper defines, models, and compares assignment strategies for a shared-use AV mobility service (SAMS). Specifically, the paper presents the *on-demand SAMS with no shared rides*, defined as a fleet of AVs, controlled by a central operator, that provides direct origin-to-destination service to travelers who request rides via a mobile application and expect to be picked up within a few minutes. The underlying operational problem associated with the on-demand SAMS with no shared rides is a sequential (i.e. dynamic or time-dependent) stochastic control problem. The AV fleet operator must assign AVs to open traveler requests in real-time as traveler requests enter the system dynamically and stochastically. As there is likely no optimal policy for this sequential stochastic control problem, this paper presents and compares six AV-traveler assignment strategies (i.e. control policies). An agent-based simulation tool is employed to model the dynamic system of AVs, travelers, and the *intelligent* SAMS fleet operator, as well as, to compare assignment strategies across various scenarios. The results show that optimization-based AV-traveler assignment strategies, strategies that allow en-route pickup AVs to be diverted to new traveler requests, and strategies that incorporate en-route drop-off AVs in the assignment problem, reduce fleet miles and decrease traveler wait times. The more-sophisticated AV-traveler assignment strategies significantly improve operational efficiency when fleet utilization is high (e.g. during the morning or evening peak); conversely, when fleet utilization is low, simply assigning traveler requests sequentially to the nearest idle AV is comparable to more-advanced strategies. Simulation results also indicate that the spatial distribution of traveler requests significantly impacts the empty fleet miles generated by the on-demand SAMS.

1. Introduction

The individually-owned and -operated vehicle has dominated passenger transportation for over sixty years in the United States (Mckenzie and Rapino, 2011). However, over the past decade, carsharing, ridesharing, and especially ridesourcing services have seen significant growth in the passenger transportation market (Clewlow and Mishra, 2017). Fully-autonomous vehicles (AVs) should accelerate the growth of these mobility services via eliminating the labor costs of human drivers and subsequently allowing shared-use AV mobility services (SAMSs) to compete with the personal (autonomous) vehicle in terms of cost, convenience, and service quality for nearly all trip purposes (Mahmassani, 2016a, 2016b). In addition to labor costs, AVs also eliminate the performance limitations of human drivers, including hours-of-service constraints and slow human reaction times.

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This paper focuses on the real-time operation/control of an SAMS fleet, as such, the most-relevant operational-level advantage of AVs is their ability to safely and near-instantaneously receive and execute changes in vehicle plans (e.g. routes, schedules, and traveler assignments) coming from the fleet operator (i.e. a central computing system). From a fleet management perspective, the biggest advantage of AVs is their guaranteed compliance with these real-time plan changes, and more generally the fleet manager's operational policies. Although it is possible to require taxi and ridesourcing drivers to follow the fleet manager's operation policies and fleet operator's real-time instructions, the fact that taxi and ridesourcing services give drivers considerable autonomy suggests that driver compliance may be too difficult to mandate and/or ineffective in practice. With complete operational control, the fleet operator can maximize the profit of the fleet rather than allowing drivers to maximize their own profit. Moreover, the fleet operator can do so with near-perfect information about the location and state of AVs and open traveler requests, as well as the ability to near-instantaneously re-plan AV routes, schedules, and traveler assignments in real-time as new traveler requests enter the system.

Motivated by the cost and performance benefits of AVs, the potential for SAMSs to compete with the personal vehicle, the ability of SAMS fleet operators to completely control individual vehicles, and the importance of operational efficiency, this paper examines the underlying operational problem associated with an *on-demand SAMS with no shared rides*. The SAMS's characteristics are as follows:

- Travelers request rides dynamically via a mobile application; a request includes pickup and drop-off locations, both within a pre-defined geographical service region
- Travelers want to be served (i.e. picked up) immediately
- Travelers will always be served, if they are willing to wait, i.e. the fleet operator cannot reject traveler requests
- AVs transport travelers directly from their requested pickup location to their drop-off location, i.e. no en-route detours to pick up or drop off other travelers
- AVs in the fleet are functionally homogeneous
- The fleet size is fixed in the short term (i.e. one-day)
- The fleet operator has complete control over each AV
- The fleet operator seeks to minimize fleet miles and traveler wait times

Aside from the vehicles being driverless and the fleet operator having complete control over the AVs, this SAMS differs from existing ridesourcing services in that it has a fixed fleet size. The fleet size is assumed to be fixed as ridesourcing companies, technology companies, and car manufacturers have stated that they plan to provide mobility services with their own AV fleet, rather than sell individual AVs to travelers (Waymo, 2017; Wingfield, 2017).

This paper focuses on the underlying problem associated with operating an on-demand SAMS with no shared rides, which is a stochastic (future traveler requests are unknown) and highly-dynamic (travelers want to be picked up soon after requesting a ride) vehicle routing problem. This operational problem shares many features with existing dynamic vehicle routing problems in the academic literature, such as the taxi- and ambulance- dispatching problems, the personal rapid transit problem, and the dynamic truckload pickup and delivery problem. However, Section 2 outlines the uniqueness of the on-demand SAMS with no shared rides operational problem. The original contributions of this paper include:

- defining the *on-demand SAMS with no shared rides* and its underlying operational problem
- modeling the on-demand SAMS with no shared rides operational problem as a dynamic AV-traveler assignment problem
- presenting intelligent optimization-based AV-traveler assignment strategies (i.e. control policies, or solution algorithms) that consider the unique characteristics of the SAMS; e.g. the ability to safely and near-instantaneously re-assign en-route pickup AVs to new traveler requests
- testing these intelligent optimization-based strategies against simple, yet common, AV-traveler assignment strategies employed in the literature and in practice.

The remainder of the paper is structured as follows. Section 2 reviews the existing literature related to SAMSs and dynamic routing problems. Section 3 formally defines the on-demand SAMS with no shared rides operational problem and presents a mathematical formulation of the AV-traveler assignment problem. Section 4 presents six AV-traveler assignment strategies. Section 5 briefly describes the agent-based simulation framework employed to model the dynamic system of travelers, AVs, and the intelligent SAMS fleet operator. Section 6 lists the experiments designed to compare the six AV-traveler assignment strategies and presents the computational results. Finally, Section 7 concludes the paper.

2. Background

2.1. Shared-use AV mobility services

Over the past five years, researchers have begun to study SAMSs, such as shared-use automated taxi (aTaxi) services (Ford, 2012), shared-use autonomous vehicle (SAV) services with and without shared rides (Fagnant and Kockelman, 2015, 2014), and automated Mobility on Demand (aMoD) services (Spieser et al., 2014). This paper uses the SAMS acronym to be as general as possible when referring to shared-use AVs providing some form of mobility service.

Existing supply-side research on SAMSs generally involves an agent-based modeling framework with three components including