



Designing optimal autonomous vehicle sharing and reservation systems: A linear programming approach



Jiaqi Ma ^{a,*}, Xiaopeng Li ^b, Fang Zhou ^c, Wei Hao ^d

^a Department of Civil and Architectural Engineering and Construction Management, University of Cincinnati, Cincinnati, OH 45221, USA

^b Department of Civil and Environmental Engineering, University of South Florida, FL 33620, USA

^c StoneRiver, Inc., OH 45241, USA

^d Transportation Engineering Department, Changsha University of Science and Technology, Changsha, Hunan 410205, China

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ABSTRACT

Autonomous vehicle (AV) technology holds great promise for improving the efficiency of traditional vehicle sharing systems. In this paper, we investigate a new vehicle sharing system using AVs, referred to as autonomous vehicle sharing and reservation (AVSR). In such a system, travelers can request AV trips ahead of time and the AVSR system operator will optimally arrange AV pickup and delivery schedules and AV trip chains based on these requests. A linear programming model is proposed to efficiently solve for optimal solutions for AV trip chains and required fleet size through constructed AVSR networks. Case studies show that AVSR can significantly increase vehicle use rate (VUR) and consequentially reduce vehicle ownership significantly. In the meantime, it is found that the actual vehicle miles traveled (VMT) in AVSR systems is not significantly more than that of conventional taxis, despite inevitable empty hauls for vehicle relocation in AVSR systems. The results imply huge potential benefits from AVSR systems on improving mobility and sustainability of our current transportation systems.

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1. Introduction

Privately owned vehicles provide incomparable mobility, flexibility, and freedom to travel. The private auto mode constitutes over 83% of the total passenger trips in the U.S.; however, they pose great challenges to transportation sustainability. Every year in the U.S., private vehicles are a major contributor to approximately 17% of household expenses allocated to transportation, 70% of the total petroleum consumption, and 30% of greenhouse gas emissions (Bureau, 2014). Additionally, private vehicles are left unused for 23 h a day (Litman, 2007) and the increased parking occupies 25% of urban surfaces (Jakle and Sculle, 2004). Public transit systems have the potential to overcome these difficulties, but they may not have as high service quality and flexibility, e.g., passenger discomfort and difficulty in accessibility (Sinha, 2003).

Vehicle sharing is an alternative to private vehicle ownership. A group of people collectively owns a number of spatially distributed vehicles (Cooper et al., 2000). This mode provides a comfort level similar to that of private vehicles and also reduces ownership significantly. Over the past decade in North America, the number of shared vehicles has increased from under 700 to over 15,000, and the number of people who use this service has grown from 16,000 to over a million (Shaheen and Cohen, 2013). Well-known vehicle sharing services include Zipcar (<http://www.zipcar.com/>), JustShareIt (<http://www.>

* Corresponding author.

E-mail address: jiaqi.ma@uc.edu (J. Ma).

justshareit.com/), Autolib (<https://www.autolib.eu/en/>) and City Car Club (<http://www.citycarclub.co.uk/>). Vehicle sharing has become a major transportation mode with high spatial accessibility and holds the promise of a future sustainable transportation system with high vehicle use rates, minimum land occupancy, significant cost savings, and likely environmental and social benefits (Millard-Ball, 2005). Traditional vehicle sharing, however, still faces one major challenge that prevents it from being widely used among the public: nearby vehicle availability. If no vehicles are nearby, a person may be stranded, thus having to wait a long time or walk a great distance. Thus, under such circumstances this person may not continue to use shared vehicles for future travels.

The emerging technologies of mobile communications and autonomous vehicles (AV) have the potential to address the previously mentioned concerns. Through connectivity using certain mobile devices, travelers can request vehicles that are relatively far away before traveling, so that they do not need to walk long distances to available vehicles. Also, different from current on-demand ride-hailing services (excluding ride-sharing), AVs can be fully self-driving and can relocate themselves automatically to any traveler's location upon request without human operations. Bansal et al. (2016) studied public opinions of and interest in new vehicle technologies (willingness to pay for adding various automation technologies and connectivity to their current and coming vehicles) using survey data from Austin, Texas. The results show a general positive attitude toward these technologies, particularly among higher-income, technology-savvy male travelers who live in urban areas, and those who have experienced more crashes. Krueger et al. (2016) conducted a targeted survey on preferences and adoption behavior of shared autonomous vehicles for a better understanding of how SAVs may be adopted. An interesting finding is that shared autonomous vehicles are considered as a separate transportation mode and young travelers with multimodal travel pattern are more likely to choose it for daily travel.

From a system performance perspective, autonomous vehicle sharing (AVS) has the potential to provide significant environmental and mobility benefits, particularly in reducing vehicle ownership and parking demands. Using an agent-based simulation approach, Fagnant and Kockelman (2014) indicate that each shared AV can replace 11 conventional vehicles though increasing Vehicle Miles Traveled (VMT) by 10%, and the sharing system results in overall benefits in regards to emissions. These benefits are approved using an agent-based simulation with pre-specified agent rules, such as how unoccupied AVs should be relocated to other zones to meet potential future demands and reduce passenger waiting times. Further, if trip demands in the next period (e.g., a day, three hours, or one hour) are known to the AVS system operator, it is possible to optimally plan AV pickup and delivery routes for all travelers ahead of time. The resultant optimal AV trip chains have the potential to provide best system performance.

In this paper, we investigate a new vehicle sharing system, referred to as autonomous vehicle sharing and reservation (AVSR). In such a system, travelers can request AVs for trips ahead of time and the AVSR system operator will optimally arrange the AV pickup and delivery before requested time and design AV trip chains on the basis of the recorded trip demand requests. Particularly, instead of relocating unoccupied AVs heuristically (e.g., to areas with less unoccupied AVs at current time), all AV routes and schedules for the next planning horizon can be optimally planned and determined. Also note that, if optimally designed, AVSR systems can provide upper bound of benefits for different AVS systems, including current on-demand ride-hailing systems (ride sharing excluded). An AVSR system has the following characteristics:

1. A fleet of AVs is distributed and shared by different users over the road network.
2. Each AV serves a passenger or a group of passengers with the same trip at a time. No ride sharing is considered. For a group of passengers with the same trip (i.e., same OD and departure time), if the number of passengers N^p in a group exceeds a vehicle's capacity C , the system will automatically consider this as $\text{ceil}(N^p/C)$ subgroups and dispatch one AV for each subgroup to meet these "separate" demands. For implementation, users can specify the number of passengers when making requests, or consider this constraint when specifying the number of vehicles to be reserved. In this paper, we assume that the subgroups have already been generated beforehand by considering the sizes of passenger groups and vehicle capacity.
3. Each trip – a pickup and delivery – is served without any interruption from other pickup and delivery jobs; thus in this paper, AVSR only considers vehicle sharing, and does not consider ride sharing.
4. There is a hard time window specified by users – the latest pickup time. This time can be the latest departure time of the user, or the user will complain if the taxi is late. Predictive technologies are available to AVSR operators to estimate potential travel times using a selected path.
5. Users make requests ahead of time, but with different request horizon options. They can request a vehicle one day before or one hour ahead of the travel. Users need to enter locations for pickup and delivery and preferred pickup time. For requests with short horizons, it is necessary to have an efficient algorithm for near real-time trip chain planning. AVSR planning needs to consider both future trips and trips that are currently being served (due to the availability of AVs at a later time when the current trip is completed).

In addition to the above AVSR characteristics, there are a few more assumptions that are made for this paper. It is assumed that each AV only returns to the depot at the end of the day for basic maintenance and preparation for the next day's service. For modeling simplicity, it is assumed that there are two virtual depots – an origin depot and a destination depot. All AVs are assigned from the origin depot and collected at the destination depot at the end of the day. This assumption does not affect the formulation and is only for modeling simplicity, and can be relaxed easily to include multiple real depots at different locations (e.g., by adding certain depot nodes and corresponding links connecting these depots and rel-

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