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Congestion-aware system optimal route choice for shared autonomous vehicles ☆

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ABSTRACT

We study the shared autonomous vehicle (SAV) routing problem while considering congestion. SAVs essentially provide a dial-a-ride service to travelers, but the large number of vehicles involved (tens of thousands of SAVs to replace personal vehicles) results in SAV routing causing significant congestion. We combine the dial-a-ride service constraints with the linear program for system optimal dynamic traffic assignment, resulting in a congestion-aware formulation of the SAV routing problem. Traffic flow is modeled through the link transmission model, an approximate solution to the kinematic wave theory of traffic flow. SAVs interact with travelers at origins and destinations. Due to the large number of vehicles involved, we use a continuous approximation of flow to formulate a linear program. Optimal solutions demonstrate that peak hour demand is likely to have greater waiting and in-vehicle travel times than off-peak demand due to congestion. SAV travel times were only slightly greater than system optimal personal vehicle route choice. In addition, solutions can determine the optimal fleet size to minimize congestion or maximize service.

1. Introduction

One of the new capabilities of autonomous vehicles (AVs) is a *shared autonomous vehicle* (SAV) service: a fleet of autonomous taxis that provide point-to-point transportation for travelers. Due to the lack of a driver, SAV costs can be similar to those of personal vehicles, and in fact previous studies have proposed replacing personal vehicles with SAVs (Fagnant and Kockelman, 2014; Fagnant et al., 2015). Because personal vehicles are unused for large periods of time, previous studies found that one SAV could replace between 3 and 11 personal vehicles (Spieser et al., 2014; Fagnant and Kockelman, 2014). SAVs have therefore received considerable attention in the literature as well as from industry.

However, a major limitation of most previous studies of SAVs is the lack of consideration of traffic congestion in their simulations. The *SAV routing problem* is the problem of finding a SAV route assignment to provide service to all travelers. For this paper, we assume SAVs carry one passenger at a time for simplicity in the already complex formulation. The SAV routing problem is similar to the well-studied, NP-hard dial-a-ride problem (DARP). The main difference is that SAVs may replace personal vehicles and become responsible for the majority of vehicle trips. Therefore, SAV routing could significantly affect congestion. Tens of thousands of SAVs may be required to replace personal vehicles on city networks. The extensive previous work on vehicle routing problems has mostly focused on scenarios in which the number of vehicles is several orders of magnitude smaller. Levin et al. (2017) incorporated an agent-based SAV model into a dynamic network loading model, and found that SAVs resulted in significantly more congestion than personal vehicles.

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The ideal solution to the SAV routing problem, which this paper addresses, is to determine SAV route choice while considering the resulting traffic congestion. The interactions between personal vehicle route choice and travel times have been extensively studied as the traffic assignment problem. The version most applicable to SAVs is DTA (DTA) (Chiu et al., 2011), as SAV trips are chained and therefore time-dependent. Ziliaskopoulos (2000) developed a linear program for system-optimal DTA. We modify their formulation to include the dial-a-ride behavior of SAVs. The resulting linear program optimally assigns SAVs to routes to pick up and drop off travelers to minimize total system travel time or other objective functions. The linear program assumes continuous flow, which is a reasonable approximation for large numbers of SAVs, but we also discuss methods of applying the formulation to routing discrete vehicles.

The contributions of this paper are as follows: we present a linear program that optimally solves the SAV routing problem, using the link transmission model (LTM) (Yperman et al., 2005) for traffic flow. This is the first system-optimal DTA formulation using LTM (as previous work has used the cell transmission model), and the use of LTM reduces the numbers of variables and constraints per link significantly. Nevertheless, the more interesting part of the formulation is the incorporation of the SAV dial-a-ride behavior. Numerical results show that peak hour travel patterns can increase vehicle miles traveled and congestion due to SAVs making empty repositioning trips. Furthermore, the optimal solution can determine the optimal fleet size to maximize service or minimize congestion. In many scenarios, the optimal solution used less than the maximum available fleet to reduce the number of active vehicles in the network. Although the linear programming formulation is not currently tractable for large networks, it may be useful for future work on the SAV routing problem.

The remainder of this paper is organized as follows. In Section 2, we review previous work on SAVs and vehicle routing problems. Next, we develop the linear programming formulation for the SAV routing problem in Section 3. Section 4 presents numerical results, and we conclude in Section 5.

2. Literature review

The models in this paper are primarily inspired by the SAV routing problem, which differs from other DARPs by the much larger numbers of vehicles and their effects on congestion. Therefore, we first discuss previous work on SAVs, which defines the SAV routing problem. Then, we frame the SAV routing problem in the context of DARP literature.

2.1. Shared autonomous vehicles

Personal vehicles currently spend many hours of the day unused while travelers are at work or engaged in other activities. Previous studies proposed that AVs could travel empty to alternate parking to avoid parking fees (Levin and Boyles, 2015a) and/or provide service to multiple household members (de Almeida Correia and van Arem, 2016). Since AVs could travel through the network without carrying any travelers, previous studies proposed a SAV system. Multiple travelers could share a single vehicle by scheduling their trips at different times (Fagnant and Kockelman, 2015a). de Almeida Correia and van Arem (2016) proposed that privately owned vehicles could provide a dial-a-ride service to multiple passengers in the same household, and developed an user equilibrium formulation. However, SAVs are not limited to trips for the owner. Owners of private AVs might offer public use for a fee, and SAVs could also be owned by taxi companies. Therefore, SAVs have evolved into a low-cost taxi or mobility-on-demand service. Without the need for a driver, service costs could approach those of personal vehicle ownership. Previous studies have therefore considered replacing some personal vehicle travel with SAVs (Fagnant and Kockelman, 2014), and have estimated that one SAV could replace up to eleven personal vehicles. Chen et al. (2016) predicted that between 14% and 39% of travelers would choose SAVs. Based on a stated-preference survey, Krueger et al. (2016) predicted SAV use among different population groups and its dependence on travel and waiting times.

Fagnant and Kockelman (2014) observed a replacement rate of one SAV for eleven personal vehicles on a grid network. Fagnant et al. (2015) studied the Austin, Texas network and demand, and found a replacement rate of one SAV for 9.3 personal vehicles. Although Chen et al. (2016) reported a replacement rate of only one SAV per 3.7 personal vehicles, they included electric SAVs that had comparable per-mile costs as personal vehicles. Burns et al. (2013) showed that a much smaller fleet of SAVs could provide service to all travelers in both urban and suburban environments. Spieser et al. (2014) found that one SAV could replace three personal vehicles in Singapore. Of course, while the number of vehicles on the road was reduced, the number of trips per vehicle was correspondingly increased to provide service to all travelers.

SAVs only carried one traveler at a time in the above studies, but Fagnant and Kockelman (2015b) and Levin et al. (2017) studied the impacts of ride-sharing on SAV travel. Zhu et al. (2016) found that ride-sharing could reduce vehicle miles traveled by 34% over conventional vehicles. Although ride-sharing could reduce costs per traveler and vehicle miles traveled (Fagnant and Kockelman, 2015b; Levin et al., 2017), it also increases travel times and potentially reduces the comfort of travel. Both factors might reduce travelers' willingness to use SAVs instead of personal vehicles. Still, travelers choosing public transit might prefer SAVs to other options for last-mile transportation (Yap et al., 2016).

Despite the attention given to SAVs, the SAV routing problem has received little attention. Previous studies have used heuristics with agent-based simulation to route SAVs, which have been sufficiently effective to showcase the potential benefits. However, most previous studies have not included the effects of SAV route choice on traffic congestion. SAV fleets large enough to replace large numbers of personal vehicles (Fagnant and Kockelman, 2014; Fagnant et al., 2015; Fagnant and Kockelman, 2015b) would have correspondingly large effects on congestion. SAV routing therefore becomes quite important