Transportation Research Part B 99 (2017) 205–227

Contents lists available at ScienceDirect

Transportation Research Part B

journal homepage: www.elsevier.com/locate/trb

On the use of reservation-based autonomous vehicles for demand management

Raphaël Lamotte[a], André de Palma[b], Nikolas Geroliminis[a,*]

[a] School of Architecture, Civil and Environmental Engineering, Urban Transport Systems Laboratory Ecole Polytechnique Fédérale de Lausanne (EPFL) GC C2 389, Station 18, Lausanne 1015, Switzerland
[b] Ecole Normale Supérieure de Cachan, CES - Université Paris-Saclay, 61, avenue du Président Wilson, 94230 Cachan, France

A R T I C L E I N F O

Article history:
Received 19 January 2016
Revised 6 January 2017
Accepted 9 January 2017
Available online 3 February 2017

Keywords:
Autonomous vehicle
Car-sharing
Vickrey's bottleneck
Advance booking
Scheduling
Stackelberg equilibrium

A B S T R A C T

Automated mobility on demand is foreseen as the future of urban passenger mobility. While mixed-traffic for autonomous and conventional vehicles could be considered, separation amplifies the benefits of automation. Combined with mobility as a service, separation also opens new possibilities in terms of demand management. We consider in this paper a single bottleneck dynamic framework, in which the capacity of a freeway is dedicated either to conventional or to autonomous vehicles. Users of conventional vehicles freely choose their departure time from home and compete for the best departure times from the bottleneck. Users of autonomous vehicles need to book their trip in advance. As the number of time slots available for booking does not exceed the capacity, booking users are guaranteed no delay at the bottleneck. An individual-specific cooperation cost is introduced in the modeling framework. We then investigate how a central planner should allocate the capacity to these two vehicle types depending on the regime (laissez-faire, welfare- or profit-maximizing). Two major findings are that the equilibrium demand split Pareto-dominates the case with only conventional cars and that the social cost difference between equilibrium and socially optimal demand splits is small compared to their benefits. Although the Pareto-improvement result may not hold for every single user in the case of richer heterogeneity, it remains a key advantage of our booking scheme. Profit-maximizing strategies however turn out to be hardly compatible with welfare maximization.

1. Introduction

Shared autonomous vehicles, also known as autonomous taxis or automated mobility on demand, are widely seen as a very likely future for urban passenger mobility. According to the International Transport Forum (2015a), it represents one of the two main pathways envisioned towards the large-scale development of autonomous vehicles, together with the gradual automatization of privately owned vehicles. For several decades already, studies have been conducted to evaluate the potential impacts of automation in fields such as road safety (Jamson et al., 2013), traffic flow on highways (Varaiya, 1993), or on urban roads (Fajardo et al., 2012; Qian et al., 2014). Yet, the potential of this mobility revolution for demand management remains largely unexplored. We investigate in this paper how a central planner should administer systems

* Corresponding author. +41216932481.
E-mail addresses: raphael.lamotte@epfl.ch (R. Lamotte), andre.depalma@ens-cachan.fr (A. de Palma), nikolas.geroliminis@epfl.ch (N. Geroliminis).

http://dx.doi.org/10.1016/j.trb.2017.01.003
0191-2615/© 2017 Published by Elsevier Ltd.

involving both conventional and bookable autonomous vehicles on separated roads. While mixed-usage environments could be considered as well, separation amplifies the benefits of automation and booking.

We consider a single bottleneck dynamic setting, in which the capacity of the freeway is divided between conventional and bookable autonomous vehicles (referred to hereafter as independent and cooperative, respectively). Users of conventional vehicles freely choose their departure time from home, while users of bookable vehicles choose in advance their time slot among those proposed by a central operator. Booking users are guaranteed no delay at the bottleneck. The main challenges addressed in this paper are then to determine how a central planner should allocate the capacity to these two vehicle types depending on the regime (laissez-faire, welfare- or profit-maximizing) and in the cases of the welfare or profit-maximizing regimes, which constant tolls/subsidies should be applied on each route. The bottleneck capacity is assumed to be perfectly divisible.

Booking is a particularly well-suited congestion management tool under unpredictable conditions. With congestion pricing, a time-dependent toll is set based on predictions of the characteristics of the population. Then, given this toll, users compete to minimize their own cost. If both the road operator and the users were able to predict perfectly the traffic conditions, queues could be avoided with appropriate time-dependent tolls (Vickrey, 1969). In practice however, the demand on a specific day is only revealed once the vehicles are on the road and have selected a departure time. Thus, the efficiency of the toll is determined by the quality of the predictions, which are notoriously difficult to make. On the contrary, booking does not rely on predictions. Time-slot booking has regularly been proposed over the last two decades as an alternative to congestion pricing for demand management (Wong, 1997; De Feijter et al., 2004; Edara and Teodorović, 2008; Liu et al., 2015). Probably because it would impose some important habit change and appears difficult to implement with conventional vehicles, it has never gained the same support as congestion pricing. Yet, the emergence of large-scale car sharing permitted by automation may challenge this status quo as booking is already well accepted for fleet management and autonomous vehicles remove the need for enforcement.

In theory, the cooperative system described could also be implemented with conventional private cars. Yet, the fact that booking has remained rather anecdotic in the literature on road congestion suggests that some important drawback has not been accounted for and prevents this development. In this work, an individual-specific cost of cooperation is introduced.[1] This cost accounts for all inconveniences related to the cooperative service, except the price, the travel time and the schedule penalties, which are modeled as in Vickrey (1969). The most important inconvenience modeled is certainly the need for users to schedule their tasks in advance. A similar cost was already proposed by Tisato (1992) and Fosgerau (2009) in the context of public transit to distinguish planning from non-planning users.

Of course, the cooperation cost is likely to depend on the flexibility that the system offers to its customers. While quantifying this effect is beyond the scope of this paper, the rapid emergence of diverse forms of mobility services involving a similar scheduling inconvenience (car-sharing, ride-sharing and, to a lesser extent, e-hailing and on-demand public transit) suggests that a significant proportion of the population is willing to bear this cost in exchange for some benefits associated with mobility as a service. Since a cooperative service would bring the additional benefit of avoiding congestion for essentially the same cost, its materialization in the context of mobility as a service seems plausible.

The proposed interpretation of the reservation service as a car-sharing system based on autonomous vehicles has important consequences from a practical point of view. First, self-driving vehicles and car-sharing systems are likely to expand together. Indeed, self-driving technologies and car-sharing are complementary: their combination allows for a door-to-door service and addresses issues related to relocation, liability and maintenance (International Transport Forum, 2015a, 2015b). Second, isolating autonomous vehicles from conventional vehicles would remove several obstacles to their development and would allow for higher capacity utilization (Varaiya, 1993), hence bringing another justification for the allocation of a reserved infrastructure. Third, self-driving technologies would naturally resolve the difficulties associated to the enforcement of the slot allocation mechanism as the vehicles would pick up their passengers only at the scheduled time. Fourth, booking also facilitates fleet management. In fact, as many car-sharing services are already reservation-based, the implementation of demand management strategies would simply bring more benefits to the current users and potentially attract new ones. In terms of our analytical results however, the only impact of automation stems from the gain in capacity associated to introducing autonomous vehicles on a separate roadway. This gain is accounted for by considering a different capacity for autonomous vehicles.

The remainder of this paper is structured as follows: Section 2 provides further details on the cooperation cost, suggests some possible interpretations for the booking service and discusses the impacts of the service on the effective capacity of the roadway. The differences with existing congestion management techniques are also highlighted. Section 3 lays the background by introducing the general assumptions and the expressions of the different costs. Then, the user equilibrium and social optimum are treated in Section 4 for both fixed capacity splits and optimal capacity splits. It is shown in particular that the user equilibrium can be made socially optimal with a simple constant toll (decentralization of the social optimum) but that unlike the social optimum, the user equilibrium with no toll and with a socially optimal capacity split Pareto-dominates the case with no cooperation. It is also shown numerically that the equilibrium and the social optimum allow very similar social cost reductions. The management of a route by a private operator is considered in Section 5 to assess the impact of profit-maximizing strategies on the social cost and finally, conclusions are drawn and suggestions for future research are stated in Section 6.

[1] If registration to the service is considered on single-trip basis, this cost would become de facto trip-specific.