– Extended Abstract –

Towards welfare optimal operation of shared autonomous vehicles

Ihab Kaddoura*, **Joschka Bischoff**

Technische Universität Berlin
Department of Transport Systems Planning and Telematics
Salzufer 17–19; 10587 Berlin; Germany

* Corresponding author (e-mail: kaddoura@vsp.tu-berlin.de)

March 7, 2017

1 Introduction and problem statement

In the last few years, research on autonomous vehicles (AVs) has increased substantially and several companies have started the development and real-world application of AVs [6, 8]. According to most studies, one shared autonomous vehicle (SAV) is capable to replace up to approximately 10 conventional (driver-controlled) private cars (CC) trips at a high service quality; the total mileage is found to increase caused by empty trips to pick up passengers [14, 4, 12, 3, 2]. In the case of pooling and depending on the fleet size, even more CC trips may be replaced by one SAV and total mileage may decrease [see e.g. 3]. Analyzing the welfare effects of a city-wide replacement of CCs by SAVs needs to account for several cost components listed in Tab. 1.

A world with AVs creates new opportunities to traffic planners and policy-makers. Instead of providing incentives to private car users by means of optimal pricing, traffic management may directly control the AV operation. In particular, in the case of SAVs, dynamic vehicle routing and dispatch strategies may aim for the maximization of overall system welfare instead of the operator's profit. This offers a crucial advantage over optimal pricing schemes for CCs.

Table 1: Welfare effects of a city-wide replacement of CCs by SAVs [see e.g. 4, 5, 1]

Capital cost	Depending on the costs of an AV compared to a CC, unit costs per vehicle may increase or decrease. A reduced car ownership may decrease total capital cost.
Operating cost	Cleaning cost and vandalism may increase the unit cost per vehicle-kilometer. In the case of electric SAV operation unit costs per vehicle-kilometer may be reduced compared to non-electric CCs. The increase in total mileage may increase total operating cost.
Travel time	On the one hand, traffic congestion caused by the increased total mileage and waiting times may increase door-to-door travel times. On the other hand, waiting may be eliminated by booking SAVs in advance, time is saved by eliminating parking search, a more fluent flow may reduce traffic congestion and a higher comfort may reduce marginal cost per in-vehicle-time.
Accidents	By avoiding the human error the accident costs may decrease.
Air pollution	Depending on the vehicle technology, air pollution costs may decrease (electric vehicles) or increase (non-electric vehicles) due to the increase in total mileage.
Noise	On the one hand, a more fluent flow and in the case of electric vehicles for low speeds, noise costs may be reduced. On the other hand, increased total mileage may increase noise costs.
Other	Reduced demand for parking allows for a new usage of public space.

Following the concept of Pigouvian taxation, the system welfare is maximized by internalizing so-called external effects [13]. By adding the external costs to the generalized travel costs of CC users, the decision-relevant travel costs are corrected and reflect the full costs associated with the usage of transport resources. However, marginal external costs vary with e.g. the road segment, the vehicle type and the time of day. Consequently, a first-best optimal tolling scheme for CC users may be difficult to be fully understood by the transport users, resulting in failing incentives and welfare losses. Furthermore, the required tolling technology for CCs may be very costly. A more simplified second-best tolling scheme may reduce tolling costs and be more comprehensible for CC users, however, also involve a loss in welfare compared to the first-best solution.

2 Methodology

This study proposes an optimal SAV operation approach which builds on the Pigouvian taxation principal. The operator's routing- and dispatch-relevant cost are extended by an estimation of the road-, user- and time-specific marginal external congestion [10] and noise cost [9]. Further externalities such as accident costs and air pollution costs are considered to be zero. The proposed optimization approach uses the agent-based and dynamic transport simulation framework MATSim[1] [7] and an existing module for dynamic vehicle routing problems [11]. In MATSim, each transport user is modeled as an individual agent. SAV users need to order a SAV, wait for the next SAV to arrive, get on the SAV and get off the SAV at the destination. SAVs and CCs interact on the same network applying a queue model which accounts for dynamic congestion and spill-back effects.

3 Simulation experiments and preliminary results

Several simulation experiments are carried out for the case study of the Greater Berlin area. In two different setups, 10% and 50% of the today's CC trips are assumed to be replaced by SAV trips. Both setups are simulated for different SAV fleet sizes and SAV operation approaches: (i) the existing operation time minimal approach and (ii) the proposed welfare optimal SAV operation approach.

Preliminary results show that the proposed optimal SAV operation is capable to increase overall system welfare by approximately 1% (10% SAV trip share) and 20% (50% SAV trip share). Average travel times decrease by 3% (10% SAV trip share) and 21% (50% SAV trip share). Noise damages decrease by 1% (10% SAV trip share) and 8% (50% SAV trip share). In contrast, operating costs increase since SAVs take longer detours in order to avoid heavily congested roads as well as noise sensitive areas. A comparison of the SAV simulation experiments with the today's traffic situation (0% SAV trip share) indicates that noise damage costs are higher due to the increase in total mileage; traffic congestion and door-to-door travel times are found to increase. The overall change in system welfare strongly depends on assumptions regarding the flow of SAVs under mixed traffic conditions as well as the valuation of time which is spent in a SAV or waiting for a SAV.

Overall, this study highlights the importance to control SAV operation, i.e. routing and dispatch strategies, to make full use of the great potential of SAVs for the improvement of a city's transport system.

[1] see www.matsim.org

References

[1] F. J. Bahamonde Birke, B. Kickhöfer, D. Heinrichs, and T. Kuhnimhof. A systematic view on autonomous vehicles: Policy aspects for a sustainable transportation planning. Technical report, German Aerospace Center (DLR), 2017.

[2] J. Bischoff and M. Maciejewski. Simulation of city-wide replacement of private cars with autonomous taxis in Berlin. *Procedia Computer Science*, 83:237–244, 2016.

[3] W. Burghout, P.-J. Rigole, and I. Andreasson. Impacts of shared autonomous taxis in a metropolitan area. In *Transportation Research Board 94th Annual Meeting*, number 15-4000, 2015.

[4] D. J. Fagnant and K. M. Kockelman. The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. *Transportation Research Part C: Emerging Technologies*, 40:1 – 13, 2014.

[5] J. B. Greenblatt and S. Saxena. Autonomous taxis could greatly reduce greenhouse-gas emissions of us light-duty vehicles. *Nature Clim. Change*, 5(9):860–863, Sept. 2015.

[6] M. Harris. Uber Could Be First to Test Completely Driverless Cars in Public. IEEE Spectrum, 14.09.2015, 2015.

[7] A. Horni, K. W. Axhausen, and K. Nagel, editors. *The Multi-Agent Transport Simulation MATSim*. Ubiquity Press, in preparation. See `http://matsim.org/the-book`.

[8] J. Hsu. Gm and lyft team up for robot taxi service. IEEE Spectrum, 04.01.2016, 01 2016.

[9] I. Kaddoura and K. Nagel. Activity-based computation of marginal noise exposure costs: Implications for traffic management. *Transportation Research Record*, 2597, 2016.

[10] I. Kaddoura and K. Nagel. Congestion pricing in an agent-based and dynamic context. VSP working paper, TU Berlin, Transport Systems Planning and Transport Telematics, in preparation. See `http://www.vsp.tu-berlin.de/publications`.

[11] M. Maciejewski. Dynamic transport services. In Horni et al. [7], chapter 23. See `http://matsim.org/the-book`.

[12] L. M. Martinez, G. H. A. Correia, and J. M. Viegas. An agent-based simulation model to assess the impacts of introducing a shared-taxi system: an application to lisbon (Portugal). *Journal of Advanced Transportation*, 49(3):475–495, jul 2014.

[13] A. Pigou. *The Economics of Welfare*. MacMillan, New York, 1920.

[14] K. Spieser, K. Treleaven, R. Zhang, E. Frazzoli, D. Morton, and M. Pavone. Toward a systematic approach to the design and evaluation of automated mobility-on-demand systems: A case study in Singapore. In *Road Vehicle Automation*, pages 229–245. Springer, 2014.