

E-Companion

Appendix A: Further Literature

A.1. The Potential Impact of MoD Systems

Over the past few years, multiple prominent studies documenting the current and expected future rise of MoD solutions have been published. A few examples of the publishers are intergovernmental organizations and national associations like the International Transport Forum (ITF, Martínez 2015) and VDV (2015) as well as leading universities, e.g., the MIT and Stanford (Alonso-Mora et al. 2017, Mitchell 2008, Pavone 2016). The ITF report, which focuses on a theoretical case study in Lisbon, has been widely discussed. The authors conduct a simulation based on real trip data and analyze the effects of introducing a fleet of self-driving vehicles on a city-wide level, once as a ride sharing system and once as a car sharing system where passengers use the same cars sequentially. These services are assumed to replace the trips currently undertaken by private car and by bus, and in one extreme scenario even today's metro trips. While this is a multimodal setup, no intermodality is considered and each trip is realized with a single mode. The outcome shows that a ride-sharing system could satisfy current demand with only 10.4% of today's car fleet. This number would only rise to 12.8% when also replacing the metro (for a car sharing system the numbers are 16.8% without replacing and 22.8% with replacing the metro, respectively). Furthermore, this could be achieved while reducing average waiting and travel times significantly.

The Association of German Transport Companies (VDV) also sees the pressure on classical public transport rising due to the additional competition by these new offers (VDV 2015). They recommend that the public transport industry acts quickly while leveraging public transport's core competency to aggregate high numbers of passengers for affordable prices.

Alonso-Mora et al. (2017) look at a similar experiment in New York and provide a mathematical model that designs the vehicle routes while still solving real-world instances. The findings, both in terms of the reduced number of vehicles required and the resulting waiting time, support those of the ITF report. Mitchell (2008) focuses more on the conceptual side and depicts a differentiated MoD concept based on a variety of vehicle types and focuses on MoD as a first or last-mile solution, i.e., on an intermodal context. Finally, Pavone (2016) analyzes a full and autonomous MoD solution, however mentions MoD as a last mile solution as a direction for future research.

In short, these studies show that MoD—in particular when combined with autonomous vehicles—has the potential to turn the urban mobility landscape upside down. This underlines the necessity for public transport operators to actively shape the process of integrating MoD and public transport systems to maintain relevance.

A.2. Operational Modeling of Mobility on Demand

Wang and Odoni (2016) focus on the last-mile problem where passengers travel from a public transport stop or station to the final destination. However, the public transport network itself is not in scope of their study. Instead, they derive analytical expressions for the expected waiting time until boarding and expected riding times and evaluate them against a simulation approach, in the first step for the unit-capacity case,

i.e., one passenger per vehicle, and in the second step for vehicle capacities up to 20. The main independent variables considered are the headway of the public transport service, the batch size of customers alighting from the train or bus, the average distance passengers travel to their final destination, the fleet size of the last-mile service, as well as additional statistical parameters. The computational studies show how expected waiting times rise when the utilization of the service increases. These insights can be used to determine an appropriate MoD fleet size to achieve a desired service level.

A similar setup for a stand-alone MoD service is analyzed by Diana et al. (2006) where the fleet size is analytically estimated based on service level requirements. The key inputs are the distribution of demand as well as time windows for the passengers. The output is then compared to a simulation model in order to validate the analytical expressions. The computational study shows how the number of required vehicles increases with a growing number of requests and for smaller time windows. Additionally, it can be observed from (Diana et al. 2006, Table 1 in Section 5.3) that the number of vehicles per request actually decreases with a growing number of requests due to better utilization, which supports our approach of carefully reflecting on utilization aspects in a strategic model.

Another modeling approach for a stand-alone MoD service can be found in (Martínez et al. 2015). Passengers with close origins and destinations are clustered in a first optimization step and assigned to vehicle routes in a second step. The last step is the maximization of the operational profit under the condition that passenger requirements on travel duration and arrival time are respected. This process also permits the determination of a suitable fleet size.

Archetti et al. (2017) present a simulation study to assess the performance of an MoD system in terms of costs, service quality, and travel time depending on demand density. Standard buses and private cars are available as alternatives and the authors simulate the mode choice of users in their approach.

The classical approach to optimize the routing of demand responsive services is focused on solving the Dial-a-Ride Problem (DARP). Surveys on the DARP are presented in (Cordeau and Laporte 2007) for literature up to 2007 and in (Ho et al. 2018) for more recent works.

References

- Alonso-Mora J, Samaranayake S, Wallar A, Frazzoli E, Rus D (2017) On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment. *Proceedings of the National Academy of Sciences* 114(3):462–467, URL <http://dx.doi.org/10.1073/pnas.1611675114>.
- Archetti C, Speranza MG, Weyland D (2017) A simulation study of an on-demand transportation system. *International Transactions in Operational Research* 25(4):1137–1161, URL <http://dx.doi.org/10.1111/itor.12476>.
- Cordeau JF, Laporte G (2007) The dial-a-ride problem: models and algorithms. *Annals of Operations Research* 153(1):29–46, URL <http://dx.doi.org/10.1007/s10479-007-0170-8>.
- Diana M, Dessouky MM, Xia N (2006) A model for the fleet sizing of demand responsive transportation services with time windows. *Transportation Research Part B: Methodological* 40(8):651–666, URL <http://dx.doi.org/10.1016/j.trb.2005.09.005>.
- Ho SC, Szeto W, Kuo YH, Leung JM, Petering M, Tou TW (2018) A survey of dial-a-ride problems: Literature review and recent developments. *Transportation Research Part B: Methodological* 111:395–421, URL <http://dx.doi.org/10.1016/j.trb.2018.02.001>.
- Martínez L (2015) Urban mobility system upgrade: How shared self-driving cars could change city traffic. Corporate partnership board report, International Transport Forum.
- Martínez LM, Viegas JM, Eiró T (2015) Formulating a new express minibus service design problem as a clustering problem. *Transportation Science* 49(1):85–98, URL <http://dx.doi.org/10.1287/trsc.2013.0497>.
- Mitchell WJ (2008) Mobility on demand: Future of transportation in cities. Smart cities, MIT Media Laboratory, URL http://smartcities.media.mit.edu/pdf/Mobility_on_Demand_Introduction.pdf.
- Pavone M (2016) Autonomous mobility-on-demand systems for future urban mobility. *Autonomous Driving*, 387–404 (Springer Berlin Heidelberg), URL http://dx.doi.org/10.1007/978-3-662-45854-9_19.
- VDV (2015) Zukunftsszenarien autonomer Fahrzeuge: Chancen und Risiken für Verkehrsunternehmen. White paper VDV, Verband Deutscher Verkehrsunternehmen e. V. (VDV), URL <https://www.vdv.de/position-autonome-fahrzeuge.pdf>, (In German).
- Wang H, Odoni A (2016) Approximating the performance of a “last mile” transportation system. *Transportation Science* 50(2):659–675, URL <http://dx.doi.org/10.1287/trsc.2014.0553>.