Sensitivity of the urban transport system to the value of travel time savings for shared autonomous vehicles: A simulation study

Benoit Lécureux[a,*], Ihab Kaddoura[b]

[a] *École Nationale des Travaux Publics de l'État, 3 Rue Maurice Audin, Vaulx-en-Velin 69120, France*
[b] *Technische Universität Berlin, Transport Systems Planning and Transport Telematics, Salzufer 17-19, 10587 Berlin, Germany*

Abstract

Shared Autonomous Vehicle (SAV) services hold potential for disruptive impacts on urban transport systems. The value of travel time savings (VTTS) for these new services is assumed to be both significantly different from that of regular services and to have a strong impact on mobility behaviors. In this study, an agent-based transport simulation for Berlin, Germany, is used to investigate the sensitivity of the urban transport system to different VTTS for shared autonomous vehicle services. Simulation experiments are carried out for a range of plausible VTTS suggested by the literature. The simulation results indicate a strong impact of the VTTS on the modal split. Overall, further research is needed to further investigate behavioral parameters as well as the resulting impact on the urban transport system.

Keywords: agent-based transport simulation; value of travel time savings; demand responsive transport; shared autonomous vehicles; activity-based demand model

1. Introduction

Innovative transport modes such as shared autonomous vehicles (SAVs) hold potential for disruptive impacts on transport systems. Overall, they are likely to provide societal benefits [5]. Agent-based models such as MATSim (Multi-Agent Transport Simulation, www.matsim.org) are suitable tools to investigate SAVs. Apart from monetary costs and the service quality, behavioral parameters such as the value of travel time savings (VTTS) determine how such services are accepted and used by the population. The VTTS is defined as the monetary value of changes in time spent in traveling, relative to an alternative use of that time [4]. It is therefore dependent on the value of money. Other known parameters influencing the VTTS include the travelers income (which will influence its alternative use of the time value), its trip purpose (since commuting generally induces more time constraints than shopping), the mode used, whether this mode includes some waiting or egress time, its comfort, and in the specific domain of shared mobility, if the mode includes sharing a trip with a stranger. A low VTTS means that the time spent traveling will be less lost and therefore tend to signal a better traveling option (all other parameters being equal). On the one hand, the VTTS may be considered to decrease for SAVs because the autonomous driving features will allow for an increase in productiveness during the trip which may also yield a modal shift towards SAVs [15]. On the other hand, people may have some concerns regarding the autonomous driving technology which may translate into an increase in the

* Corresponding author
E-mail address: benoit.lecureux@entpe.fr

VTTS. Since current studies on SAVs mainly rely on very specific assumptions, there is a need to explore the impact of the VTTS on the SAV demand as well as the overall transport system. The goal of this study is to identify a range of plausible VTTS for SAVs and to use the agent-based simulation framework MATSim to analyze the sensitivity of the urban transport system in Berlin, Germany, to the changes in VTTS.

2. Literature review

[17] investigate the travelers' preferences for Autonomous Vehicles (AVs) with a focus on last-mile transport of multimodal train trips. They conclude that first class travelers prefer the use of AVs compared to bicycle or public transit (PT), and that the sensitivity of travelers for in-vehicle time is higher for an automatically driven AV, compared to a manually driven one. The authors suggest that unfamiliarity and discomfort of AVs might play a role in these results. The authors widen their investigations in [18] to the impact of travelers' attitudes to the reliability and sustainability of AVs. [12] assess characteristics of users who are more likely to adopt SAV services (young and multimodal travelers). They measure the VTTS for dynamic ride-sharing SAV services and individual SAV services, being respectively 90% and 70% of the willingness to pay for conventional cars. [10] address current and future choices of users. Their results indicate that users incomes have an important impact on the VTTS and that trip purposes influence mode choice. The VTTS are found to be lower for both private cars and SAVs compared to conventional cars. In [16] the previous study is extended by a new econometric model. The results show that autonomous driving may lead to a reduction in the VTTS for commuting trips (of 31% for private vehicles and 10% for SAVs). In [11], the authors use a new joint-mixed logit model on the same data collection. The results show a VTTS reduction of 41% for private autonomous vehicles compared to conventional cars for commuting trips. No significant changes in the VTTS are found for other purposes, or for SAVs. [3] go from the assumption that AVs could lead to reduced VTTS because of the ability to perform in-car activities. They explore whether the interior design of the AVs might have an impact on VTTS for commuting trips. Their results show that AVa designed to perform office activities might have a lower VTTS than conventional cars (-25%), whereas those designed for leisure have a higher VTTS (+29%). In [6], an existing ride hailing service (RHS) is used as an analogy for the non-existing SAV services and the VTTS is found 13% lower for RHS compared to driving a conventional car. They also find that mentioning that the RHS is driver-less leads to a 15% increase of the VTTS, and that if the ability of in-vehicle multitasking is explicitly mentioned the VTTS is cut to its half compared to a conventional car. Those two studies highlight the perception biases in the assessment of VTTS. [1] try to overcome this biases by conducting a survey based on a two-step AVs adoption process, first for shared or pooled vehicle services, including PT feeder services, then for private autonomous vehicles, for short and long trips. They conclude to a lower VTTS for shared and pool autonomous vehicles services (resp. -39% and -30%) compared to private cars. An overview of several studies is provided in Tab. 1.

Overall, the literature review reveals that the VTTS for new SAV services does not seem to be clearly higher or lower compared to the VTTS for conventional driver-controlled services. The VTTS for private autonomous vehicles is in most cases smaller than the VTTS for non-pooled shared autonomous vehicle services. And the VTTS for non-pooled shared autonomous vehicle services is smaller than the VTTS for pooled shared autonomous vehicle services. Also the trip purpose plays an important role. For commuting with AVs, the VTTS is in most cases below the VTTS for conventional services (including driving a private car), whereas for leisure/shopping activities, VTTS seems to be higher with AVs than with conventional services.

Study	Variable_name	Conventional Car	Private AV		Shared AV (without pooling)		Shared AV (with pooling)		Discrete Choice Model	Focus_Group	Country	Year
		VTTS	VTTS	*Relative attractiveness*	VTTS	*Relative attractiveness*	VTTS	*Relative attractiveness*				
Valuation of travel attributes for using automated vehicles as egress transport of multimodal train trips [17]	Willingness-to-pay in €/10mn	1,85	-	-	2,3	*1,243*	-	-	MNL*	Representative of the Dutch travellers	Netherland	2015
Preferences of travellers for using automated vehicles as last mile public transport of multimodal train trips [18]	Willingness-to-pay in €/10mn	1,6	-	-	2,05	*1,281*	-	-	MNL*	Representative of the Dutch travellers	Netherland	2015
Estimation of the value of time for autonomous driving using revealed and stated preference methods [10]	Value of time in €/h	2,84	1,29	*0,454*	1,96	*0,690*	-	-	MNL*	Low incomes	Germany	2017
Estimation of the value of time for autonomous driving using revealed and stated preference methods [10]	Value of time in €/h	4,49	1,99	*0,443*	3,02	*0,673*	-	-	MNL*	Middle incomes	Germany	2017
Estimation of the value of time for autonomous driving using revealed and stated preference methods [10]	Value of time in €/h	4,72	2,73	*0,578*	4,14	*0,877*	-	-	MNL*	High incomes	Germany	2017
How Autonomous Driving May Affect the Value of Travel Time Savings for Commuting [16]	Value of travel-time savings in €/h	5,39	3,74	*0,694*	4,85	*0,900*	-	-	ML** + Box-Cox	Commuters only Low incomes	Germany	2018
How Autonomous Driving May Affect the Value of Travel Time Savings for Commuting [16]	Value of travel-time savings in €/h	6,6	4,59	*0,695*	5,94	*0,900*	-	-	ML** + Box-Cox	Commuters only Middle incomes	Germany	2018
How Autonomous Driving May Affect the Value of Travel Time Savings for Commuting [16]	Value of travel-time savings in €/h	10,36	7,2	*0,695*	9,32	*0,900*	-	-	ML** + Box-Cox	Commuters only High incomes	Germany	2018
Assessing the effect of autonomous driving on value of travel time savings a comparison between current and future preferences [11]	Value of travel-time savings in €/h	6,4	3,8	*0,594*	6,2	*0,969*	6,7	*1,047*	ML** + pseudo-panel	Commuters only Low incomes	Germany	2019
Assessing the effect of autonomous driving on value of travel time savings a comparison between current and future preferences [11]	Value of travel-time savings in €/h	7,8	4,6	*0,590*	7,7	*0,987*	8,2	*1,051*	ML** + pseudo-panel	Commuters only Middle incomes	Germany	2019
Assessing the effect of autonomous driving on value of travel time savings a comparison between current and future preferences [11]	Value of travel-time savings in €/h	11,2	6,6	*0,589*	11	*0,982*	11,8	*1,054*	ML** + pseudo-panel	Commuters only High incomes	Germany	2019
Assessing the effect of autonomous driving on value of travel time savings a comparison between current and future preferences [11]	Value of travel-time savings in €/h	3,9	3,9	*1,000*	6,2	*1,590*	6,7	*1,718*	ML** + pseudo-panel	Leisure/shopping only Low incomes	Germany	2019
Assessing the effect of autonomous driving on value of travel time savings a comparison between current and future preferences [11]	Value of travel-time savings in €/h	4,8	4,8	*1,000*	7,7	*1,604*	8,2	*1,708*	ML** + pseudo-panel	Leisure/shoppingonly Middle incomes	Germany	2019
Assessing the effect of autonomous driving on value of travel time savings a comparison between current and future preferences [11]	Value of travel-time savings in €/h	6,9	6,9	*1,000*	11	*1,594*	11,8	*1,710*	ML** + pseudo-panel	Leisure/shoppingonly High incomes	Germany	2019
Preferences for shared autonomous vehicles [12]	Value of travel-time savings ratio (compared to car)	-	-		-	*0,700*	-	*0,900*	ML**	Residents of major metropolitan areas	Australia	2016
Potential changes in value of travel time as a result of vehicle automation: a case-study in the Netherlands [3]	Value of travel time in €/h	8,37	6,26	*0,748*	-	-	-	-	Taste ML**	Vehicle interior settled for office duty	Netherlands	2018
Potential changes in value of travel time as a result of vehicle automation: a case-study in the Netherlands [3]	Value of travel time in €/h	8,37	10,82	*1,293*	-	-	-	-	Taste ML**	Vehicle interior settled for leisure	Netherlands	2018
Would being driven by others affect the value of travel time? Ridehailing as an analogy for automated vehicles [6]	Value of travel time in $/h	24,47	-	-	21,32	*0,871*	-	-	ML**	If driven by Taxi driver	US	2019
Would being driven by others affect the value of travel time? Ridehailing as an analogy for automated vehicles [6]	Value of travel time in $/h	24,47	-	-	28,03	*1,145*	-	-	ML**	If driven by a Ride Hailing System WITHOUT driver	US	2019
Would being driven by others affect the value of travel time? Ridehailing as an analogy for automated vehicles [6]	Value of travel time in $/h	24,47	-	-	13,42	*0,548*	-	-	ML**	If driven by a Ride Hailing System WITHOUT driver that favours multitasking	US	2019
Predicting the use of automated vehicles for Zurich, Switzerland [1]	Value of travel-time savings in CHF/h	17,143	-	-	10,59	*0,618*	12	*0,700*	NL***	-	Switzerland	2018

**MNL = Multinomial Logit **ML = Mixed Logit ***NL = Nested Logit*

Table 1. Review of the VTTS for SAVs.
Since most transport models are calibrated for the todays modes of transportation (e.g., car, PT), all VTTS found in this review have been translated into a relative attractiveness compared to car (VTTS for the considered mode / VTTS for the conventional car mode).

3. Methodology: MATSim (Multi-Agent Transport Simulation) and the Open Berlin Scenario

MATSim is a framework for an agent-based model, where each agent consists of a travelers plan (a daily pattern of activities and travels). Each agent has individual properties and acts autonomously, which opens the possibility of modeling the increasing diversity of transports services and policies [7] [19]. The initial travel plans evolve through an evolutionary iterative approach; a repetition of the following steps enables the agents to improve their set of plans and approximates the stochastic user equlibrium.

1 Traffic Flow Simulation: plans are executed in a traffic flow simulation. Congestion and vehicle movements are simulated applying a queue model. Each road segment (link) is modeled with certain attributes (free speed travel time, flow capacity, storage capacity) and the transport users interact in the simulated physical environment.
2 Scoring: for each agent, the executed plan is scored based on agent-specific predefined behavioral parameters and scoring functions. A plans score typically consists of two parts: (i) the generalized travel cost or trip-related disutility (e.g. travel time, toll payments) and (ii) the utility gained from performing activities.
3 Learning: for most of the agents, the plan to be executed is chosen in a short list via a multinomial logit (mode choice model). For a part of the agents, the set of available plans is first amended by a modification of an existing plan (choice mode, route, hours of depart or arrival).

This study is based on the MATSim **Open Berlin Scenario**, described in [19]. This scenario is based on the Berlin metropolitan area and the demand for transport is synthetically recreated from various census and population open datas (no information from a travel diary survey is required as input, to facilitates reproducibility for other regions). To reduce computation times, this study uses a downscaled scenario with a population sample of 1.0 percent.

In MATSim, the VTTS takes into account both the specific cost of traveling (with the marginal utility of traveling β_{travel}, which can be specific to a mode - see Equation 1) and the decrease in utility from having less time available to perform an activity (marginal utility of performing β_{perf}) [8]. Assuming that an agent performs all activities for their typical duration, a trips VTTS can be computed as $VTTS = \left(-\beta_{travel} + \beta_{perf}\right) / \beta_{money}\big)$.

The **MATSim's DRT module** has been used to simulate SAV services in numerous studies [see e.g. 14, 13, 9]. The SAV mode is designed as a ride hailing service with pooling which offers a door-to-door service. Agents request their ride just before the trip. Waiting time is computed and included in their generalized cost (with a specific VTTS-like parameter). The requested ride is assigned to the vehicle which can serve it with the least additional operation time needed to serve the requested ride [2]. A fare is paid by the agent for using the service. SAVs are simulated in traffic (with conventional vehicles).

Simulation experiments. Based on the literature review, depending on the purposes of travel and other parameters, the relative attractiveness of SAV compared to car ranges from 0.443 to 1.718. Therefore, simulations are run for a range of a modified marginal utility of traveling for the SAV mode, equivalent to a decrease of -50% in the VTTS to an increase of +50%. It seemed not useful to increase the VTTS to +71,8%, since increasing the VTTS for the SAV mode makes it more unlikely to be used, to a point where it is barely chosen anyway. Also, simulation experiments were not run with a decrease of VTTS below -50%, since such an extreme improvement is considered as unlikely. The simulation was run several times for different behavioral parameters for a total number of 500 iterations to allow each agents plans to converge to the individual optimum. The β_{travel} parameter was set on a range from -3 (i.e. +50% VTTS) to +3 (i.e. -50% VTTS) with a +0.6 (i.e. -10%) increment for each new simulation. Besides, as it is considered likely that VTTS would decrease for SAV services, around -30% for non-pooled, and -10% for pooled services [16], the increment was set to +0.3 (i.e. -5%) between 0 and +3. The minimum fare per trip is set to 2.0 EUR, and distance fare is set to 0.35 EUR per kilometer. The SAV fleet size is set to 1000 vehicles with each a capacity of 4 seats.

4. Results and discussion

As expected, a decrease in VTTS for SAVs leads to a shift toward this mode. The strongest decrease in VTTS for SAVs yields an SAV share of 5.5% (see Fig. 1). The relative low modal share for SAV in comparison to the other modes is explained by the service area which is limited to the city of Berlin and the considerably high fares. PT and bicycles are the modes mostly affected by the modal shift towards SAV. They lose up to 2% of modal share (about 8% and 16% of their total), while the modal share for car decreases by only 0.3% (less than 1% of its total).

This might be due to the fact that the service area was too small and that most people using a car, also have trips to or from outside the service area.

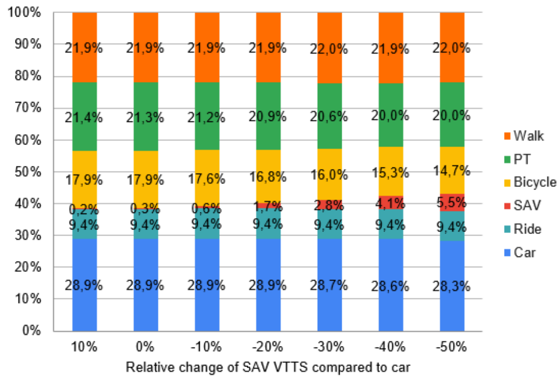

Fig. 1. Modal split (Greater Berlin area) depending on the VTTS for SAV

Fig. 2 depicts the evolution of the modal split throughout the 500 iterations. The first mode to be affected is the PT mode which quickly loses a large part of its modal share (and often regain a little bit of it along the iterations), while bicycle first gain some users, before slowly losing them to the SAV mode (or car, depending on the scenario). The average distance traveled by a customer increases with the reduction of the VTTS from less than 4 kilometers to 5 kilometers a day. At the same time, in-vehicle time increases and waiting time first decreases and then stabilizes. For the SAVs, reducing the VTTS seems to first decrease the emptiness ratio (the percentage of kilometers traveled without passengers) from 35% to 20% and then stabilizes around the level of 18% when the decrease in VTTS exceeds 25%.

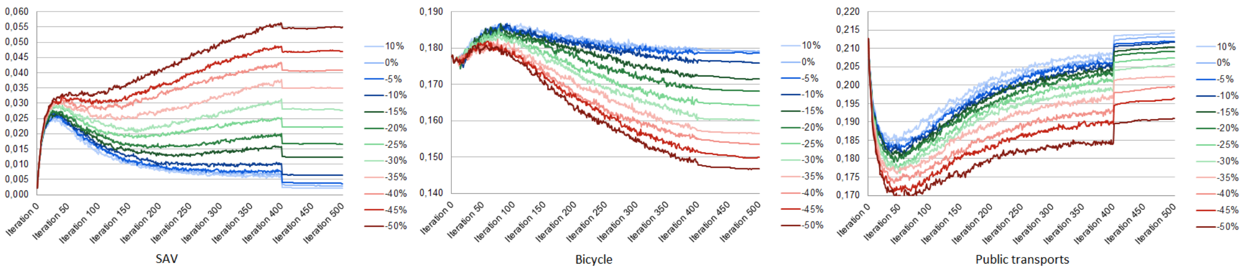

Fig. 2. Modal shares per iteration for SAV, bicycle and Public Transit *(the percentages refer to the relative change in VTTS for the SAV mode)*

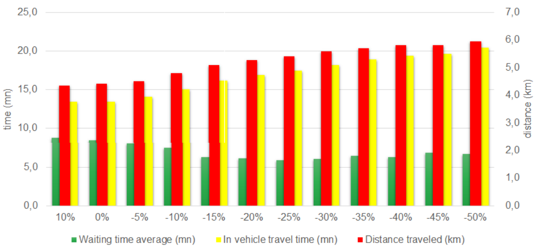

Fig. 3. Time and distance traveled by customer *(in min and km)*

Reduced fare scenario. To investigate the impact of the SAV fare level on the results of the VTTS sensitivity analysis, simulation experiments are carried out for a reduced minimum fare of 1.0 EUR. Structurally, the results look similar and the VTTS is found to have a strong impact on the total SAV trip number. With this fare reduction, the SAV trip share yields 2.8% in the base case (no change in VTTS for SAVs). For a change in VTTS of -50%, the modal share for SAV climbs up to 8.5%. The share of users using a combination of PT and SAV, mostly non-existent in the 2.0 EUR minimum fare scenarios, represents up to 2.6% in the 1.0 EUR minimum fare scenario for -50% VTTS.

5. Conclusion and outlook

Overall, the VTTS for SAVs is found to have a strong impact on the modal split. The total trip share in the Greater Berlin area for the SAV mode climbs up from below 1% to 5.5%. For the reduced fare the SAV trip share increases from 2.8% to 8.5%. This evolution of the modal split has its strongest impact on the PT and bicycle mode. A decrease in the VTTS for SAVs also has a positive impact on the service efficiency, reducing its emptiness ratio, and on consumers experience (reducing the weight of waiting time in the total travel time).

However, questions remain: The literature review on VTTS has highlighted the difficulty for users to grasp the possible features of SAV. To get a better understanding of future travel behavior, it is very important to carry out real-world experiments and to further investigate user preferences. Also, some studies suggest that VTTS only decrease for long trip durations to allow for some productive activities to take place inside the vehicle. For short trips common in urban areas with a spatially limited SAV service area, the change in VTTS might be of small magnitude. However, for larger SAV service areas, long-distance commuters and rural areas, the VTTS for SAVs may significantly decrease. Overall, studies on future SAV services should account for a plausible range of the future VTTS in combination with other decision-relevant parameters such as the service quality or fare level.

Acknowledgments

The first author would like to thank the entire team at the department of Transport Systems Planning and Transport Telematics at Technische Universität Berlin for their support throughout this work, especially Prof. Kai Nagel and Dominik Ziemke for their guidance through the first steps of MATSim.

References

[1] Becker, Axhausen (2018) "Predicting the use of automated vehicles for Zurich." *International Conference on Travel Behavior Research*.
[2] Bischoff, Fhrer and Maciejewski (2018) "Impact assessment of autonomous DRT systems." *International Scientific Conference on Mobility and Transport*
[3] de Looff, Correia, van Cranenburgh, Snelder and van Arem (2018) "Potential Changes in Value of Travel Time as a Result of Vehicle Automation: a Case Study in the Netherlands." *Transportation Research Board 97th Annual Meeting*
[4] Edwina (2019) "What is the Value of Saving Travel Time?." *https://www.itf-oecd.org/what-value-saving-travel-time*
[5] Fagnant and Kockelman (2015) "Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations." *Transportation Research Part A: Policy and Practice* **77** : 167–181.
[6] Gao, Ranjbari and MacKenzie (2019) "Would being driven by others affect the value of travel time? Ridehailing as an analogy for automated vehicles." *Transportation* **46** (6) : 2103–2116.
[7] Horni, Nagel and Axhausen, (2016) "The Multi-Agent Transport Simulation MATSim." *Ubiquity, London* doi:10.5334/baw.
[8] Kaddoura and Nagel (2016) "Agent-based Congestion Pricing and Transport Routing with Heterogeneous Values of Travel Time Savings." *Procedia Computer Science* **83** : 908–913.
[9] Kaddoura, Leich and Nagel (2020) "The impact of pricing and service area design on the modal shift towards demand responsive transit." *Procedia Computer Science* **170** : 807–812.
[10] Kolarova, Steck, Cyganski and Trommer (2018) "Estimation of the value of time for automated driving using revealed and stated preference methods." *Transportation Research Procedia* **31** : 35–46.
[11] Kolarova, Steck and Bahamonde-Birke (2019) "Assessing the effect of autonomous driving on value of travel time savings: A comparison between current and future preferences." *Transportation Research Part A: Policy and Practice* **129** : 155–169.
[12] Krueger, Rashidi and Rose (2016) "Preferences for shared autonomous vehicles." *Transportation Research Part C* **69** : 343–355.
[13] Leich and Bischoff (2019) "Should autonomous shared taxis replace buses? A simulation study." *Transportation Research Procedia* **41**.
[14] Maciejewski and Bischoff (2017) "Congestion effects of autonomous taxi fleets." *Transport* **33** (4) : 971-980.
[15] Narayanan, Chaniotakis and Antoniou (2020) "Shared autonomous vehicle services: A comprehensive review." *Transportation Research Part C: Emerging Technologies* **111** : 255–293.
[16] Steck, Kolarova, Bahamonde-Birke, Trommer and Lenz (2018) "How Autonomous Driving May Affect the Value of Travel Time Savings for Commuting." *Transportation Research Record* **2672** (46) : 11-20 .
[17] Yap, Correia and van Arem (2015) "Valuation of Travel Attributes for Using Automated Vehicles as Egress Transport of Multimodal Train Trips." *Transportation Research Procedia* **10** : 462-471.
[18] Yap, Correia and van Arem (2016) "Preferences of travellers for using automated vehicles as last mile public transport of multimodal train trips." *Transportation Research Part A: Policy and Practice* **94** : 1–16.
[19] Ziemke, Kaddoura and Nagel (2019) "The MATSim Open Berlin Scenario: A multimodal agent-based transport simulation scenario based on synthetic demand modeling and open data." *Procedia Computer Science* **151** : 870–877.