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EXPLORING THE INFLUENCES OF AUTOMATED SHUTTLES ON MOBILITY PATTERN AND TRAFFIC SYSTEM AT DIFFERENT GRANULARITY LEVELS

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ABSTRACT

This paper shows the abilities of MATSim and SUMO to reflect the real-world behavior of automated shuttles (AS) and their applicability to replicate and evaluate scenarios. Possible impacts of introducing AS at street- and city-level were investigated regarding the permitted low operating speeds of AS. Two simulation studies in Salzburg, Austria, and in Linköping, Sweden, were conducted. Together with the real pilot plans, different scenarios, considering operational speed, frequency and service type, were addressed. No significant impacts on the respective traffic systems were revealed, even though AS operated at a low speed (15-20 km/h). It is mainly due to the relatively low traffic density and other characteristics of the selected routes. Higher travel speed and Demand-Responsive-Transport operation help to improve the efficiency of AS and to increase the public acceptance. Though, additional push measures are needed to change the domination of cars in a rural setting for influencing modal shift.

1 INTRODUCTION

A good public transport (PT) offer is a major backbone for sustainable mobility. Yet, public transport is usually expensive and the major costs are named to be the personnel costs of drivers (Hörcher and Tirachini 2021). Automated shuttles (AS) promise a solution to this problem. As valid for any new technical system nowadays, their introduction should be prepared by simulations. Simulating the introduction ex-ante allows to measure the changes in mobility patterns to expect as well as the costs and the benefits of the introduction, to reveal possible problems or bottlenecks, and to scale the system properly for fulfilling the posed requirements at the lowest possible costs. Within the European project SHOW, 70 automated vehicles (AVs) were introduced in the public transport systems at the selected real-world pilot sites, where more than half of the AVs were AS. This has been scientifically accompanied and evaluated (SHOW 2024). Besides the surveys and evaluations of the collected data, simulations were a part of the process, and simulations have been performed before and after the introduction of AS within the pilot sites.

This paper presents and discusses two examples of using simulations within the SHOW project. In both cases, AS were in focus, yet with different research questions: (1) How would the introduction of AS, especially at low speed, influence the road traffic efficiency; and (2) How would the introduction of AS affect the transport mode choice. On the one hand, the effects of introducing AS and demand-responsive transport (DRT) on mode choice were investigated. On the other hand, simulating the interactions between AS and other traffic participants were modelled both on normal roads and in a shared space and compared against real-world measurements. The concept of shared spaces describes a part of the road network where all modes – pedestrians, bicyclists and public transport and delivery vehicles, sometimes motorized individual traffic as well – share the same infrastructure, often without any markings and rules constraining e.g. the direction of passing an area. Safety issues are targeted by lowering the allowed maximum velocity and by mutual attention. More and more AS are deployed in shared spaces. It is therefore important to understand the potential impact of AS in these areas. In both case studies, different scenarios were developed and evaluated to get more insights on the impacts on mobility and traffic to expect, regarding different operational circumstances of AS in accordance to the proposed research questions. Of course, a proper representation of the dynamics of the AS within the simulations is needed.

The remainder is structured as following. First, the current state of the art in simulating the impacts of automatic public transport vehicles and shared spaces is given in Section 2. Section 3 describes how the two project pilot sites, namely Salzburg, Austria, and Linköping, Sweden were replicated with the open source simulation tools Multi-Agent Transport Simulation (MATSim) (MATSim 2024) and Simulation of Urban MObility (SUMO) (Alvarez Lopez et al. 2018), respectively. After that, the research questions, the scenarios and the results are presented and explained in Section 4. Conclusions and next steps are given at the end.

2 STATE OF THE ART

Traffic models have been used for planning purposes since the early 1950ies (McNally 2008). The most prominent approach for computing the mobility within an area and subsequently the resulting traffic amounts is the four-step-model (Ortúzar and Willumsen 2011). Four-step-models are macroscopic – they compute the aggregated measure traffic flow, the number of vehicles passing a road, usually within a day. Due to using this aggregated output measure as well as aggregated input data, they are criticized to be incapable to replicate differences in the behavior of individual participants and/or vehicles (McNally and Rindt 2007). In the context of the SHOW project, this means that no differences between the on-road behavior of conventional and of automated vehicles could be considered.

The shortcomings of the aggregation and the increasing computing power led to an increase in using so-called microscopic models. The demand, the number of rides people want or need to perform, can be computed by so-called agent-based demand models (Zheng et al. 2013), where each person is represented by her/his sociodemographic attributes and chooses a daily activity plan, the locations to visit for following it, and the mode(s) of transport to access these locations. The assignment and the simulation of the vehicles' progress through the road network is then computed using microscopic traffic simulations where each vehicle is represented individually again, including a set of attributes like its length, maximum velocity or acceleration, among other. In case of simulating AVs these attributes have to be chosen in accordance to these vehicles' behavior in the real world, including further rules or parameters for resembling their specifics, if necessary.

Various simulation-based studies on the impacts of AS and on-demand systems have been performed in the past. Oh et al. (2020) used stated preference (SP) surveys for their simulations of a one-way ride sharing system with AS and simulate the demand by performing dynamic requests to vehicles and adapting the vehicles' routes. One of their findings was that vehicle kilometers travelled decreased by 50% after the introduction of the service. Alazzawi et al. (2018) used a SUMO simulation for Milan to model the impact of AS. They found that a 50% transition rate towards the shuttle service was required to achieve a significant reduction in traffic. According to another study by Vosooghi et al. (2019), the majority of autonomous shuttle users were formerly public transport users, car users or pedestrians, with the most significant decline in usage observed in the public transport sector compared to cars and walking. The modal shift towards AS ranged from 1.5% to 4.4% with two significant values for fleet sizes of 2-3k and 7k vehicles.

More and more AS operate in shared spaces in practice. This results in the increasing need to properly simulate AS travelling in such areas. Several models, e.g. Anvari et al. (2015), Pascucci et al. (2015), Schmid (2018), Gibb (2015), Olstam et al. (2020), have proposed solutions for simulating road users in shared spaces. However, these solutions either (1) only focus on shared space areas, (2) are not fully implemented for general use yet or (3) are not freely available. In conventional road traffic simulations, no shared spaces are considered and road users do not regard other road users' movements in opposite direction. To make up for this gap, Flötteröd et al. (2023) proposed the concept bidirectional edge and implemented it in SUMO, as a part of the sub-lane road user simulation model. The model is included in SUMO from the version 1.15.0 onwards. Flötteröd et al. (2023) also calibrated and compared the simulated results with real-world measurements collected in a shared space. The respective results were quite promising. However, more data and tests are still needed for handling various traffic situations. This bidirectional-edge concept and the implemented behavior functions have been adopted to realistically simulate the shared corridor in the case Study Linköping and to evaluate the proposed scenarios in this paper.

3 PILOT SITE REPRESENTATION IN THE SIMULATION

3.1 Tool Specifications and Characteristics

MATSim is an open-source framework used for simulating transportation systems by representing the traffic demand through agents, i.e. individuals who are either traveling on the network or performing an activity at a fixed location in the simulation area. The dynamic/kinetic characteristics of each vehicle type are not considered. Instead, the progress through the road networked is computed using a queue-based approach. MATSim is designed to simulate the individual perspective of travelers and their interactions with the transportation infrastructure by running over multiple simulation iterations until a system equilibrium is reached. In each of the iterations, the agents evaluate the score of their daily schedule consisting of time for travel, usually negatively scored and the positively scored duration of a performed activity. Details to the scoring in MATSim can be found in (Horni et al. 2016), p.23ff. Between iterations, agents are randomly selected to either change their routes while keeping the same mode of transport, choose a different mode of transport for their trips, or randomly select one of the plans performed in previous iterations, with those having a higher score being picked with a higher probability. An equilibrium is established over the iterations, providing information on how the changed mobility behavior adjusts.

SUMO is a microscopic multi- and intermodal traffic flow simulation, released as open source in 2002, and is in continuous development since then. SUMO is used for a large range of applications, including the optimization of traffic assignment, the development and evaluation of new methods and systems as well as for planning purposes. In comparison to MATSim, SUMO simulates agents' behaviors and interactions with different models for e.g. car following, lane changing, pedestrian movements, signal control and the interactions at junctions for simulating each road user's dynamics. Changes in transport mode choice and the issues related to vehicle communication, emissions and energy consumption can also be addressed with SUMO. Besides the traffic simulation application, SUMO also includes many tools, e.g. for network and demand preparation, simulation data processing, or visualization.

3.2 Simulation Set-Up – Salzburg Pilot Site

The Salzburg pilot site included a DRT service with AS for a peri-urban region, connecting it to the city center via an intermodal mobility exchange, bridging the first/last mile using automated shuttles. A city-wide simulation was run to evaluate the impacts of such DRT services on the modal split of the served areas as well as the effects of DRT on public transport use in the area. The network comprises the city of Salzburg, large parts of the state of Salzburg, the German Corner (road network only) and small parts of Upper Austria. From the national transport survey of Austria (Tomschy et al. 2016), a 33% population sample was created that includes socio-demographic characteristics as well as the activity chains of the individuals. The infrastructure capacity was reduced along with the population accordingly. The decision to consider only a 33% sample was made to ensure reasonable computation times, although Kagho et al. (2022) recommended using a 100% sample, as results with smaller samples tend to overestimate the use of DRT. For DRT, an agent-to-vehicle matching was performed, which was no longer linearly proportional to the sample size in this study. It should be noted that the results for a 100% sample would be overestimated, if the results were tripled. The modes of transport available in the MATSim model are walking, cycling, public transport, and car. For the Salzburg pilot site, six rural regions in the proximity of the city (10-30 km away) were chosen as the use case for the introduction of AS, as shown in Figure 1. In one scenario (scenario A in Table 2), the service was also tested with actual shuttles run with a predetermined schedule rather than as DRT.

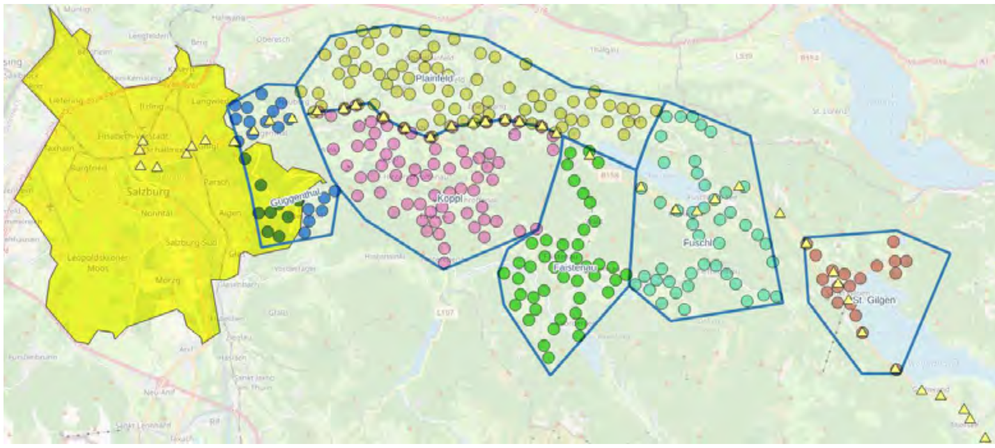


Figure 1: Simulation area for the Salzburg use case. The six areas where the DRT service was implemented are marked by blue lines and located east of Salzburg (yellow area). A bus line with several stops (yellow triangles) connected these areas with the city. The DRT service was implemented as a stop-based DRT service (dots) in scenarios B-G shown in Table 2, whereas in scenario A, only a small bus line was tested in the area of Koppl (pink dots), which is not indicated on the map (map source: OpenStreetMap).

An important parameter for the simulation is the acceptance of the new shuttle service. Since no SP surveys have been conducted in the simulation area, data from the literature was referred. In line with several studies, it was assumed that the value of travel time savings (VTTS) associated with riding a shared automated electric vehicle is similar to the VTTS of a car passenger, whereas Lu et al. (2018) found no differences in the VTTS between drivers and passengers of a car, and Fosgerau (2019) and Ho et al. (2015) concluded that the VTTS for a passenger can be regarded as about 75% of the rate for car drivers. For the AS in Salzburg, we followed the assumption that they are perceived as part or enhancement of the public transport service and therefore set the VTTS of AS (DRT) to the VTTS of PT which is about 50% of the VTTS of cars in our mode choice model. Parameters for the mode choice model for the DRT vehicles followed the approach described in (Greene and Henshe 2003). A Latent Class Mode Choice Model (LCMCM) was estimated on data containing weekly activity diaries and expenditure data from a representative sample in Austria (see (Hössinger et al. 2020)). The variables deciding on class membership in the LCMCM were gender, age under 35, age over 55, income higher than the median, schooling higher than the median, living in an urban area, children in the household, single household, and working full-time at least 38 h per week. Since MATSim does not allow for agent-specific models, the LCMCM was used to separate the population into 10 subpopulations of equal size and the parameters for these groups were calculated by averaging over the parameters of the subgroup members. Furthermore, the parameters for the mode choice behavior were given by mode-specific constants, the VTTS, and the value of leisure (VoL), which refers to β_{dur} in the Charypar-Nagel function. Other disutilities such as waiting times or transferring public transport were set as given in (Müller et al. 2021), in which also some justification for the separation in ten subpopulations is given. Table 1 contains the parameters for the Charypar-Nagel function in (Horni et al. 2016) as set in the model.

The cost of owning and driving a car followed the estimates from ADAC (Müller et al. 2021) for average vehicles. The fixed cost of a car was assumed to be 13.521 EUR per day excluding an additional expenditure of 0.091 EUR per kilometer driven. Bicycle costs were estimated to be 1 EUR per day. Public transportation travel costs for agents without a concession card or an annual ticket card were manually configured by taking the average of station-to-station fares. All financial expenditures were direct disutilities in the utility function in case the mode has been used at least once.

Table 1: VTTS of all modes for each of the ten subpopulations of agents of the MATSim model for Salzburg. The parameters refer to the mode choice parameters as they appear in (Horni et al. 2016), pp.24ff.

Subpop	c_{bike}	c_{car}	c_{pt}	β_{bike}	β_{car}	$\beta_{pt}=\beta_{AS}$	β_{walk}	$\beta_{timeSwitch}$	β_{dur}
0	2.55	0.85	0.14	−9.39	−12.20	−5.29	−11.07	−0.71	10.71
1	2.72	0.80	0.13	−10.50	−12.29	−5.47	−11.39	−0.75	9.34
2	2.86	0.76	0.12	−11.40	−12.36	−5.61	−11.66	−0.78	6.49
3	2.95	0.74	0.12	−12.01	−12.40	−5.71	−11.84	−0.80	9.11
4	3.05	0.70	0.11	−12.70	−12.46	−5.82	−12.04	−0.83	6.82
5	3.18	0.67	0.11	−13.55	−12.52	−5.95	−12.29	−0.86	10.77
6	3.28	0.64	0.10	−14.22	−12.57	−6.06	−12.49	−0.88	10.23
7	3.43	0.59	0.10	−15.21	−12.64	−6.21	−12.78	−0.92	7.25
8	3.67	0.52	0.09	−16.82	−12.77	−6.47	−13.26	−0.98	6.17
9	2.55	0.85	0.14	−9.39	−12.20	−5.29	−11.07	−0.71	10.71

3.3 Simulation Set-Up – Linköping Pilot Site

The Linköping pilot site of the SHOW project was located in city of Linköping, Sweden, on the Linköping university campus and the adjacent residential area, with a fairly low traffic density. The pilot activity aimed to improve the travelling experiences of PT users, children and the elderly. Two AS provided scheduled transport services at the fixed bus stops every day. Along the 4 km long shuttle route (see Figure 2), the AS not only ran in mixed traffic on ordinary roads and exclusive bus lanes, but also in a bidirectional shared corridor, where cyclists and the AS shared the cycle path in the middle. In this corridor, pedestrians usually walked on both sides and could freely cross the bike path. There were also several parking lot entrances and exits on the shuttle route. To investigate the possible impacts introduced by AS, SUMO was used to set up the simulation environment for simulating the interactions between AS and road users. The parking lots on the campus, the local busses and their bus stops were replicated in the simulation as well.

Figure 2: The AS route and the planned stops at the Linköping pilot site (map source: Google Maps).

Furthermore, collected traffic data was used to adjust the traffic density at the site. Across the whole network, there were 1296 vehicles, 353 pedestrians, 618 bicycles during the afternoon peak period. 517 vehicles, 434 bicycles, 228 pedestrians and 72 busses travelled on the shuttle route and on the adjacent roads. To reflect the movement flexibility of cyclists and pedestrians in reality, they could adapt their routes on the way according to the traffic conditions they faced.

To properly reflect reality and create representative scenarios, the maneuver parameters of the shuttle, related to e.g. driving imperfection, speed, weight, ac- and deceleration, and the shuttle's physical size were adapted. The respective calibration work was carried out with use of the collected shuttle data (Gugsa Gebrehiwot 2021). Moreover, the speed, acceleration and speed factor parameters to simulate other road users in the shared space were also adapted (Flötteröd et al. 2023). The applied parameter setting was as follows: speed deviation = 0.08 m/s and speed factor = 1.05 for AS, and speed deviation = 0.4 m/s and speed factor = 1.45 for bikes, while the ac- and decelerations of AS were set to 0.45 m/s^2 and 0.48 m/s^2 with the use of the Intelligent Driver Model (IDM). The above parameters were defined within SUMO's attribute <`vType`> in a separated XML-file as input. More information about the parameter definition can be found in (SUMO 2024). According to the reported driving speed data of AS, the general speed was around 7-8 km/h for the whole route. The difference between the speeds of the simulated AS and the AS operating in reality, was mainly due to unexpected obstacles and technical issues on the route, which is in line with the reports of the safety operators. Such unexpected issues can also influence other road users, but are difficult to address in the simulation due to their low probabilities compared to incident-free time.

4 SCENARIOS AND RESULTS

Several research questions and the associated scenarios have been formulated and targeted to better understand the traffic impacts caused by AS. Together with the calibration work to create representative scenarios, the research questions and the results of the simulations that addressed them are explained below.

4.1 Salzburg Pilot Site

The idea of the scenario set up for the Salzburg pilot site simulation (see Table 2) was to see the limits in the uptake of DRTs with a growing saturation of DRT vehicles in the area. This helped to see the overall potential of introducing DRT services in a rural setting without adding push measures to limit car commuting into the city. The different shares of DRT vehicles in the zones (one vehicle, 5%, 10%, 15% and 20%) were also considered to represent a slow introduction of vehicles into the market in the best way.

Table 2: Overview over the scenarios of the Salzburg pilot site.

Scenario	Content
Baseline	The current traffic situation without AS.
Scenario A	Set-up of the baseline scenario with additional 6 automated shuttles connecting remote areas to the connector bus to Salzburg.
Scenario B	Service area-based DRT services for 6 service areas with one DRT vehicle per service area. The DRT vehicles should mostly serve as a last mile service and trips needed to start and end within one of these service areas.
Scenario C	Setup like in Scenario B; within this scenario all stops were active but only 5% of stops in the area had a DRT vehicle stationed at the beginning of the day for all service areas with a DRT vehicle.
Scenario D	Setup like in Scenario B where 10% of stops per service area had a DRT vehicle stationed at the beginning of the day.
Scenario E	Setup like in Scenario B where 15 % of stops per service area had a DRT vehicle stationed at the beginning of the day.
Scenario F	Setup like in Scenario B where 20 % of stops per service area had a DRT vehicle stationed at the beginning of the day
Scenario G	Area-based DRT service where all stops in all service areas of scenario B had a DRT vehicle stationed at the beginning of the day.

The results in Figure 3 and Figure 4 show that, without further push measures, the uptake of AS was small. Since the DRT services were only offered in certain areas, it could not be expected that the modal split of the entire area changes significantly. However, even for trips starting or ending in the study area east of Salzburg the modal split of DRT has reached at most 8%. This is due to the fact, that even with a better connection to the major bus lines, the trips including DRT still took longer than trips by car. A closer look into the modal shifts shows that DRT trips often replaced shorter trips including those that were taken by bike in the baseline. However, there has been still a reduction of about 6% of car trips for the trips starting and ending in the study area.

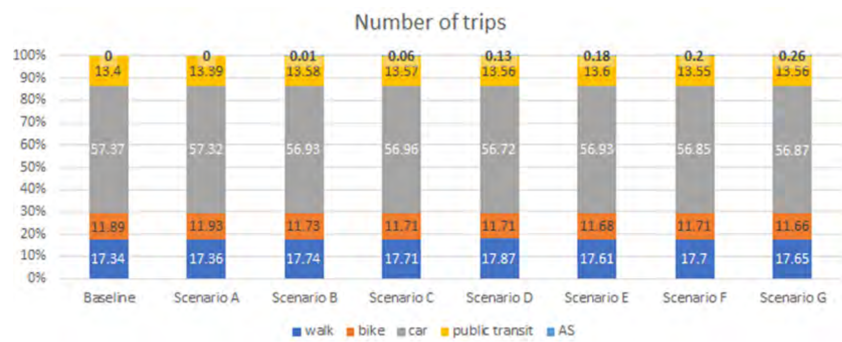


Figure 3: Modal Split by number of trips for each scenario of the Salzburg pilot site.

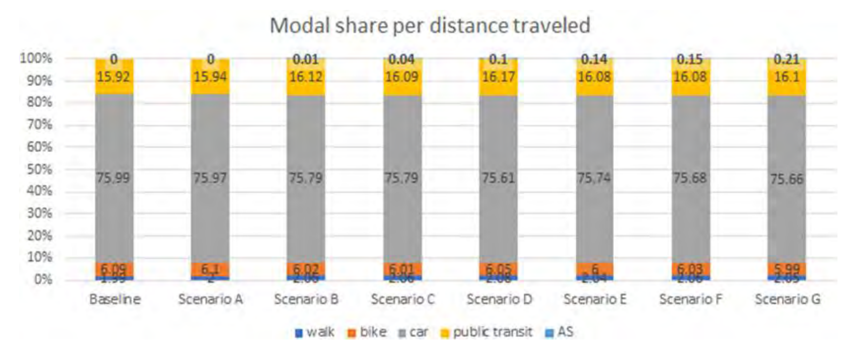


Figure 4: Modal share per distance traveled for each scenario of the Salzburg pilot site.

When comparing the results of the different scenarios, one can see in Table 3 that, with fewer AS, these had to travel further, leading to higher empty ratios. In addition, in scenario G, one can see that the AS drove a smaller distance overall than in the case with fewer vehicles, suggesting that only smaller detours would be necessary once a larger number of shuttles were available. This leaded to smaller waiting and travel times for the passengers and as a result to higher occupancy rates in the DRT vehicles, rising from 1.03 in scenario B to 1.55 in scenario G.

Table 3: Transport indicators for the AS service in the scenarios of the Salzburg pilot site.

Scenario	Total distance traveled [km]	Total empty distance [km]	Empty ratio
Scenario A	-	-	-
Scenario B	576.26	243.97	0.35
Scenario C	2381.66	1034.17	0.41
Scenario D	5215.16	2126.41	0.37
Scenario E	6573.19	2543.43	0.34
Scenario F	6778.34	2507.97	0.33
Scenario G	6423.80	1323.05	0.17

4.2 Linköping Pilot Site

In terms of the traffic system, the primary concern with the introduction of AS is the extent to which they would affect the surrounding traffic and environment. Currently, AS have to drive with a lower speed than regular road speed limit due to safety reasons. By increasing the frequency of operation, passengers' waiting times can be shortened and the shuttle service can be made more attractive. A flexible scheduling shall ensure an efficient operation in the long run. But passenger demand still needs to be fulfilled at the same time. Accordingly, the focus was put on speed and operation frequency to further investigate the influences on the traffic system performance. In addition to the base scenario without AS (Scenario 0), six scenarios were developed with the given constraints that 3 AS are available and the speed limitation on campus is 30 km/h. An overview of the proposed scenarios area is listed and explained in Table 4.

Table 4: Overview of the scenarios at the Linköping pilot site.

Scenario	Content
Scenario 0	The current traffic situation without AS as the baseline scenario
Scenario 1	It was based on Scenario 0 with 2 AS, running every 10 minutes, (i.e. 6 runs per hour), at a maximum speed of 15 km/h, and serving at the pre-defined stops.
Scenario 2 (pilot plan)	It was based on Scenario 0 with 2 AS, running every 20 minutes, (i.e. 3 runs per hour), at a maximum speed 15 km/h, and serving at the pre-defined stops.
Scenario 3	As Scenario 2, but only 50% of the stops were served.
Scenario 4	As Scenario 2, but the maximum travelling speed was increased to 30 km/h, i.e. the speed limit in this area, and the AS run every 10 minutes, (i.e. 6 runs per hour).
Scenario 5	As Scenario 4, but the AS run every 20 minutes (i.e. 3 runs per hour).
Scenario 6	As Scenario 5, but only 50% of the stops were served.

The scenario analysis result with respect to speed is illustrated in Figure 5. It clearly shows that the AS speed increased when the number of served stops was reduced and that the higher speed limit significantly contributed to the higher AS speed, as expected. For the other users, there were no apparent speed differences between the scenarios. When further examining the speed difference for other users, Figure 6 shows that the AS, running at a lower speed and higher operation frequency (scenario 1), had a relatively greater impact (around 5%) on the average speed of the vehicles, some of which left the parking lots and some of which entered, left or traveled through the campus. When the operation frequency of AS increased (scenario 2) or the number of served stops decreased (scenario 3), the respective impact declined. With the speed limit of 30 km/h, the AS had very little influence on other users' travelling speeds. Overall, the speed changes for other road users were quite small, within 5%. This limited impact is mainly due to the low traffic density in the case study area, and because a part of the AS route was located in the shared space and on a bus-only lane. In both cases, motorized individual traffic was not significantly affected by the AS.

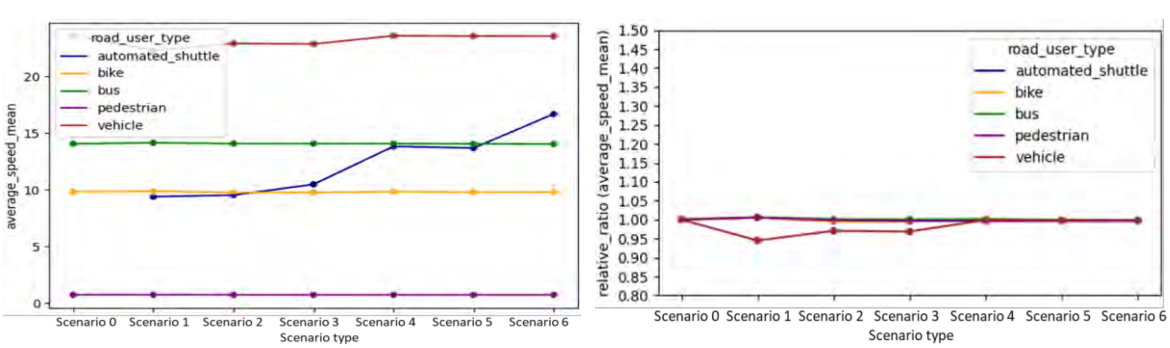
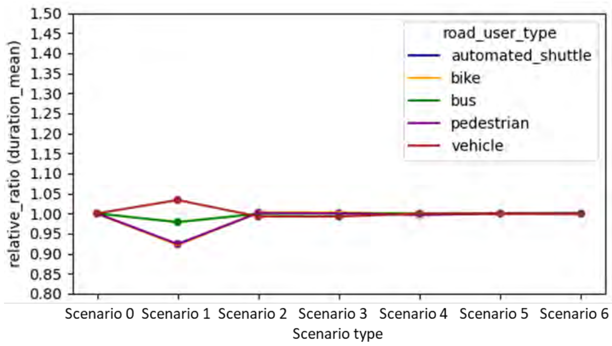


Figure 5: Average speeds and their relative ratios per road user type between the scenarios.

Moreover, Figure 6 (left) shows the relative ratios of the travel times between the scenarios. The situations for other road users generally corresponded to those based on the average travel speeds mentioned above. The changes in travel times between the scenarios were marginal except in scenario 1. When the AS operated at a low speed, but from every 20 min to every 10 min, the average travel durations of the bikes and pedestrians declined. This could be because some of them adapted their routes, which made the respective route lengths shorter (as shown in Figure 6 (right)). Due to the network structure, the route adaptation of the vehicles was limited. This increased the corresponding travel time under the situation where more AS were travelling at a low speed.



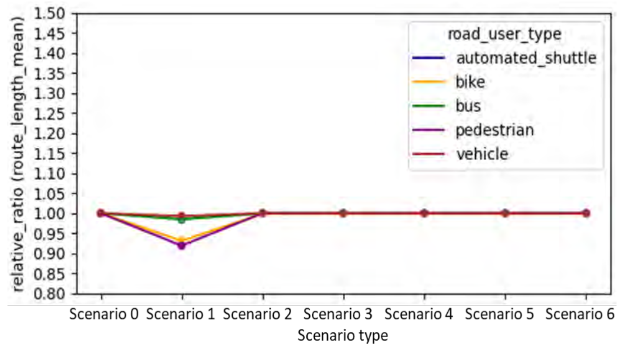


Figure 6: Relative ratios of average duration (left) and route length (right) between the scenarios.

In addition, the average waiting counts and times were analyzed. These two indicators were operationalized as the number of times and the time during which the speeds of the vehicles were below or equal to 0.1 m/s respectively. Figure 7 shows that there was no significant change in the waiting counts for other road users except the AS. As the permissible travel speed increases, the number of waiting times tended to decrease. Waiting times were influenced by the arrival times of the AS at the intersections and the traffic situation at/within the intersections they faced. Especially the waiting times at the intersections were affected by the different operation frequencies and allowed speeds in the scenarios. The result shows that both the busses and the AS had longer waiting times (around 57 sec/bus and 50-90 sec/shuttle) than other road users. This is mainly because the busses and AS could wait for the green light at the signalized intersections, whilst most other vehicles entered and left from the other parts of the site where the intersections were prioritized. According to the planned routes and the observation the buses and the AS passed the signalized intersections twice and three times per run respectively, and the places where they often waited were at the intersections. When AS operated at 30 km/h and only needed to serve 50% of the stops, the average waiting times declined to 50 sec.

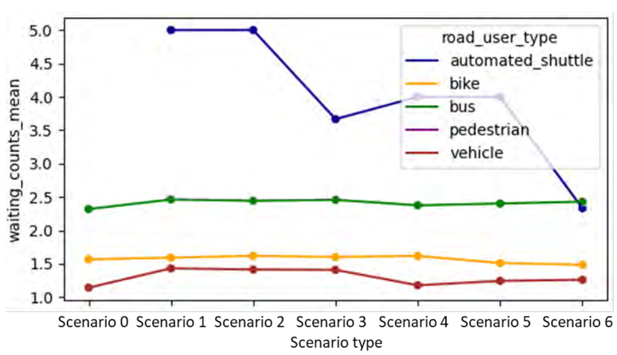


Figure 7: Average waiting counts per road user type between the scenarios.

5 SUMMARY AND PROSPECTIVES

The results from the two case studies show the abilities of MATSim and SUMO to replicate real-world behavior of AS and their applicability to replicate and evaluate different scenario settings, which is especially important when introducing changes in a transport system, e.g. a new transport mode or management strategies. Both tools can also deliver traffic-related performance KPIs and have the capacity to simulate emissions, energy consumption and charging activities.

Within the SHOW project, we have broken the rule of unidirectional roads in SUMO to consider the bidirectional lane-sharing situation of AS and other road users in shared spaces. Related overtaking and yielding maneuvers in shared spaces can also be reflected. This feature was further enhanced to better deal with the interactions of road users and applied to carry out the study in this paper. More data is still needed for testing and validation as well as for further model extension. Apart from handling the limitations of the unidirectional edges, AS have been modelled and their representation will be continually refined as well as the pedestrian and bicycle models used in SUMO. AS are currently implemented in MATSim as regular DRTs. Due to the nature of the model, it cannot accurately represent detailed driving behavior, which is why other impacts of automated vehicles on traffic, such as traffic flow, need to be further analyzed. Regarding the modelling of mode choice, it is crucial that revealed preferences studies should be performed as soon as the service is running.

Overall, the analysis results for the both pilot sites showed that there were limited impacts on traffic under the different AS scenarios. This is mainly due to the limited site size, relatively low traffic density at both sites as well as the site/route characteristics. The shuttle at the Salzburg pilot site travelled on rural roads. At the Linköping pilot site, about 50% of the AS route was either in the space only shared with free-moving bicycles, or on an exclusive bus lane. At the ordinary roads, there was a bus bay at each bus stop. Thus, vehicles have the possibility to pass the slow running shuttles. It implies that proper road design/usage should also be considered when planning routes for AS. Still, the results indicate that higher travelling speeds of AS and DRT operation help to improve AS operation efficiency and reduce the traffic impact brought by AS. This could help to increase public acceptance and willingness to use the new offers. Furthermore, adding a DRT service in a peri-urban setting influences the modal split, mainly within the DRT regions, but it does not change the domination of cars in a rural setting without adding additional push measures (e.g., parking restrictions, city tolls) to support the switch away from motorized individual transport to public transport for longer trips. New data on such push factors might be necessary to really assess the change that could be achieved. In addition, it might be helpful to look into the automation of current public transport lines to allow for denser timetables in rural areas at least on the main routes to support the introduction of DRT for more flexibility in PT.

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