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Potentials of Autonomous Vehicles in a Changing Private Transportation System – a Case Study in the Stuttgart Region

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Abstract

The extensive market introduction of autonomous vehicles will be revolutionary for traditional transportation systems. Especially today's clear boundaries between private and public transportation systems will blur. Due to the possibility of an autonomous relocation of cars, car-sharing will become more relevant and compete the protected taxicab market in Germany. Private car ownership might even become redundant. Having these possible future circumstances in mind, we use a microscopic travel demand model to simulate the mode choice behaviour in a case study for the Stuttgart region: we presume a world without private cars and the presence of a large autonomous mobility on demand (AMOD) service instead. Following, under the assumption that up to four persons share a ride, we calculated the number of cars needed to run the AMOD service smoothly.
We show that not all trips, previously made by private car, are substituted by the AMOD service; the modal share of walking, public transportation and bicycling is increasing as well. Due to lower cost of the AMOD service compared with car trips, trip lengths increase as well. The results show that about 45% of all vehicle movements and 20% of all vehicle kilometres could be saved. Furthermore, the results show that about 85% of all vehicles in the Stuttgart region might be dispensable.

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Keywords: autonomous vehicle, mobility on demand, travel demand simulation, agent-based simulation

1. Introduction

The breakthrough of autonomous vehicles (AV) is no question of 'if' – it is a question of 'when'. Hence, the big research topics are the impacts of AVs on different fields of transportation e.g. on travel behavior, as well as on traffic flow assuming level 5 of automation. Autonomous vehicles have obviously advantages such as a higher safety

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level, reduced emissions due to optimized speed and car-to-car/car-to-infrastructure communication, as well as more mobility options for disabled, younger, or older people and using the riding time for other activities, e.g. working or reading. Especially in large urban areas, these advantages of AVs in addition with information and communication technologies may change transportation from private cars towards autonomous mobility on demand (AMOD) services as a new kind of public transportation. Vehicles can be used more efficiently regarding use of space and waiting times. At the same time, cost efficiency will increase since no driver is needed and the relocation of vehicles is automated as well. These advantages offer many new possibilities for carpooling in combination with AVs. In this paper, we analyze the effects of a possible AMOD service, assessing the necessary number of cars and changes in car mileages.

In this case study, we assume a future scenario with 100% AVs in a well-working AMOD system in a world without private cars. We use the travel demand model *mobiTopp* to simulate the travel demand for this scenario for the Stuttgart region with 2.3 million agents over a period of one week. Based on the O-D-demand of the model, we determine the number of AVs which would be necessary in order to cover the mobility needs of the Stuttgart population without adapting their travel.

2. Literature Review

AVs as well as mobility on demand (MOD) services have been a huge research topic within the past years as they both promise many advantages towards the usage of conventional private owned vehicles. Besides technical issues, recent work also dealt with issues in many other fields. Fagnant & Kockelman (2015) addressed policy issues discussing the impacts of AVs. They conclude that AVs have the potential to reduce crashes, ease congestion, reduce parking needs and much more. In another discussion, Boesch & Ciari (2015) state that the impact of AVs on mobility might be huge and therefore have to be modelled in a microscopic simulation framework where travelers and cars are modelled individually. Cyganski, Fraedrich, & Lenz (2015) did a qualitative research about the modal shift potential and the potential use of travel time using autonomous vehicles.

Currently, a hot topic is to investigate AMOD services. In general, four issues regarding AMOD services are addressed: the number of cars needed, relocation issues and waiting times. Bischoff & Maciejewski (2016), for example, used the agent-based simulation MATSim (Balmer, Meister, & Nagel, 2008) to simulate a city-wide replacement of private cars by autonomous taxis based on the demand of all car trips in Berlin. Martinez, Correia, & Viegas (2015) also simulated an autonomous taxi system using a self-developed platform. Shen & Lopes (2015) compare different car scheduling strategies using the Expand and Target algorithm and the simulation platform Mobility Testbed (Čertický, Jakob, Píbil, & Moler, 2014). Using the same Mobility Testbed, Čertický, Jakob, & Píbil (2015) analyzed waiting times of AMOD travelers. There are more studies targeting more or less the aforementioned issues (Shen & Lopes, 2015; Zhang & Pavone, 2016). Spieser, Treleaven, Zhang, Frazzoli, Morton, & Pavone (2014) also investigated financial benefits of AMOD systems. Fagnant & Kockelman (2014) used an agent-based approach to investigate the environmental implications of shared autonomous vehicles considering also their relocation needs. Still, none of them did consider any changes in mode and destination choice behavior.

Davidson & Spinoulas (2015) consider AVs in a macroscopic travel demand model. They analyzed different scenarios by varying the AV share, the trip increase as well as the vehicle operation cost. They showed that more trips in the future and lower costs by electric driven AVs have an impact on the modal share as well as on the trip lengths. However, they did not consider the impact of AMOD services.

To the authors' knowledge, there is no work considering both, changes in travel behavior and AMOD services. Our microscopic multi agent travel demand model *mobiTopp* is able to show changes in destination and mode choice for a simulation period of one week. With this model results, we are able to evaluate an AMOD service in the course of one week regarding changes in travel times as well as cars needed.

3. *mobiTopp* framework

mobiTopp (Mallig, Kagerbauer, & Vortisch, 2013) is an agent-based travel demand model and is able to simulate the travel demand over a period of one week. It consists of two stages, the long-term stage and the short-term stage. The long-term stage models the features that are stable over a longer period. It comprises the population synthesis, the assignment of activity schedules, the assignment of work and education place, the modelling of car ownership and transit pass ownership. The short-term stage models the actual activity-travel behavior.

Population synthesis is based on an iterative fitting approach (Beckman, Baggerly, & McKay, 1996) using the variables household size and number of cars at the household level and age group, sex, and employment status on the level of persons. Actual households are generated using weighted random draws from a household travel survey. Workplaces and education places are assigned based on existing commuting matrices taking the travel distance reported in the household survey into account. The number of cars is a result of population synthesis, the actual type of the cars is modelled by a car ownership model (Weiss, Heilig, Mallig, Chlond, Franke, Schneidereit, et al., 2017) Transit pass ownership is determined based on a binary logit model.

The short-term stage models activities, destination choice and mode choice of the all agents and the movement of the agents and cars chronologically and simultaneously. The movement of agents and cars, however, is only modelled coarsely from zone to zone using travel times generated by an external macroscopic traffic assignment. The central part of the short-term stage is the simulation of the destination choices and the mode choices.

When the simulation starts, each agent is at home performing an at home activity. When the activity is finished the agent makes a destination choice for next activity and a mode choice for the trip to this activity. Afterwards he makes a trip to the destination. When the destination is reached the agents starts performing the activity. When the activity is finished the cycle repeats until all activities in the course of one week are finished.

The destination choice and the mode choice are based on a nested logit model. This model is separated into a destination choice part and a mode choice part using the decomposition of the joint probability into a marginal and a conditional probability:

$$P(\text{Destination}, \text{Mode}) = P(\text{Mode} \mid \text{Destination}) \cdot P(\text{Destination}) \tag{1}$$

The availability of the different modes in different situations is handled by a mode availability model, which provides a meaningful choice set of modes. Mode availability is relevant for the destination choice and as well for the mode choice. In the base version, *mobiTopp* differentiates between the modes walking, cycling, public transportation, car as driver, and car as passenger. An extension provides the additional modes station-based carsharing and free-floating carsharing (Heilig et al., 2017).

When the agent is at home, all modes are available. However, the mode car driver is only available, when the agent holds a driver's license and there is a car available in its household. When the agent is not at home, the set of available modes depends on the mode used before. If the mode used before is one of walking, public transport, or car driver, these modes constitute the set of available modes. If the mode used before is cycling or car driver, the set of available modes contains only the mode used before. *mobiTopp* contains an extension that makes the mode car as passenger available only when a ride-sharing option exists (Mallig & Vortisch, 2015), however this extension has not been activated for the work described here.

The result of a *mobiTopp* run is a trip file that contains all trips of the simulated agents with origin and destination, mode used, start and end time over the simulation period of one week.

4. Scenario Description & Methodology

In this section, we present the scenario and the methodology we used for the evaluation of an AMOD service as substitution for private cars. We performed two steps.

4.1. Step 1: Destination Choice & Modal Shift

In this step, we used the *mobiTopp* model to simulate the travel demand for the Stuttgart region. We used two scenarios: a base scenario which simulates the current situation and a future scenario which considers the AMOD service. These model results are the basis for our analysis of the AMOD service.

One can expect a change in modal shift and destination choice of the agents caused by the severe changes of mobility supply in the future scenario. Hence, we considered possible changes in the simulation of the future scenario: a scenario without private cars and with the mode “AMOD service”. Since we had no reliable data for this future mode, we simply assumed that the conditions of an AMOD service are comparable to the existing mode “car as passenger”. In both modes, travelers do not have control over the car and drive with other travelers. Further, we had to define costs for the mode “car as passenger”, since it is originally assumed as complimentary. Burns, Jordan, & Scarborough (2013) estimated a cost reduction per mile driven of up to 30% for an AMOD fleet with middle sized sedan cars and up to 60% for an AMOD fleet of small cars. Based on a heterogeneous fleet structure, we assumed a cost reduction of 45%. With an occupation rate of 1.64 passengers per car, we determined a cost reduction per mile of about 70% compared to a private car for the AMOD service. We applied this cost to the mode “car as passenger” in the future scenario. The modified choice set also has an impact on destination choice due to the combined destination and mode choice model of *mobiTopp*.

4.2. Step 2: AMOD services

Using the results of the scenarios (see Section 4.1), we investigated relevant changes for the infrastructure needed. Therefore, we estimated vehicle kilometers and trips that could be saved given the future scenario of the Stuttgart region. The scenario contains only passenger trips. Taking a “standard” car with a capacity of four passengers as a basis, car trips could be saved due to vehicle sharing of people sharing origin and destination at a certain time slot within the week.

Therefore, we analyzed the future scenario output data and first grouped trips by origin and destination, based on the zones of the *mobiTopp* model. Further, we divided the week into 672 time slots of 15 minutes each. As a consequence, all trips starting within a time slot sharing the same origin and destination are pooled together. Following, the number of vehicles per zone and time slot that are required to make these trips is calculated as followed:

$$\#\text{vehicles} = \left\lceil \frac{\#\text{trips}}{4} \right\rceil \qquad (2)$$

Given the example of five trips, two vehicles are required. The 15-minute slot size causes the travelers a mean waiting time of 7.5 minutes to start the trip. In reality, vehicles can start their trips as soon as the vehicle has four passengers and waiting times would probably be lower. However, this will not be further investigated in this paper. Using the setting as described, we can investigate both the vehicle trips and kilometers that could be saved as well as the number of vehicles that could be saved due to carpooling measures.

4.2.1. AMOD services – Vehicle trips and kilometers

To investigate trips as well as kilometers that could be saved due to carpooling, we compare the number of all car-trips before and after the pooling measures. Therefore, we use the output of the base scenario with the *mobiTopp* standard setting where private vehicles are still integrated and can be used. Vehicle trip savings are investigated comparing only car trips (without passenger trips) and the number of autonomous vehicles trips. The overall kilometers saved are the sum of the lengths of all vehicle trips saved.

4.2.2. AMOD services – Amount of vehicles needed

To further analyze the data, we first added trip distances and average travel times to the origin-destination data. Travel times are then converted to slot-level. Trips within one zone are assumed to take one slot – i.e. vehicles are available again in the following slot. For every time slot and every zone, we have the number of vehicles leaving the zone (departures) as well as the number of vehicles arriving in the zone (arrivals). Hence, we can calculate the number of vehicles that are needed to fulfil the demand given by the departures. If the departures exceed the sum of arrivals and the number of AVs that are already in the zone, additional vehicles are created for that zone. Otherwise the remaining vehicles stay in the zone until they are needed or relocated.

To determine the minimum number of vehicles that are needed to perform all trips, assumptions about empty vehicles trips are important. Empty vehicle trips are relevant because the demand does not necessarily meet the ongoing location of autonomous vehicles. In our approach, vehicle relocations are performed only during nighttime. Therefore, we assume the system to know the demand for the next day and then relocate the vehicles during the night when the demand is the lowest (i.e. around 3 a.m.). For the calculation of relocations per day we use the following equations:

$$\#surplus\ vehicles = \sum_{zone=1}^{1174} max \quad (stock_{zone} - demand_{zone} ;0) \tag{3}$$

$$\#missing\ vehicles = \sum_{zone=1}^{1174} max \quad (-1*(stock_{zone} - demand_{zone}) ;0) \tag{4}$$

$$\#relocations = min \quad (\#\ surplus\ vehicles ;\#\ missing\ vehicles) \tag{5}$$

with

$stock_{zone}$= vehicle stock at the beginning of the day in that zone

$demand_{zone}$= vehicle demand at the end of the day in that zone

The number of relocations (4) is given by the minimum of surplus vehicles (i.e. vehicles that are not needed in a specific zone to determine the next day's demand) and missing vehicles (i.e. vehicles that are needed in a zone to fulfil the demand of the next day). Hence, the minimum number of vehicles is given by the day with the highest demand since we relocate the vehicles every night.

In reality, the optimum number of needed vehicles may be less than the calculated number because the relocation process can be done during the whole day. But we have to consider that during the day "empty" autonomous cars which drive for relocation may affect the traffic flow negatively.

5. Results

5.1. Results of Step 1: Destination Choice & Modal Shift

Fig. 1 shows the modal shifts for the base and the future scenario. Not considering changes in modal shift in the future scenario would have yielded to a modal share of the AMOD service in sum of the shares of the two car modes (as driver and passenger) in the base scenario (around 65%). Looking at the results for the future scenario, for most travelers, removing all private cars indeed results in switching to the AMOD service. However, some travelers chose one of the other three mode options (walking, bicycle or public transportation). Hence, not having considering modal shifts would have resulted in an overestimation of the modal share of the AMOD service.

Due to the combined destination and mode choice model, there are also changes in destinations choice resulting from the new mode choice set. Fig. 2 shows that the distances of car trips increase. This might be caused by the lower trip costs compared to private cars.

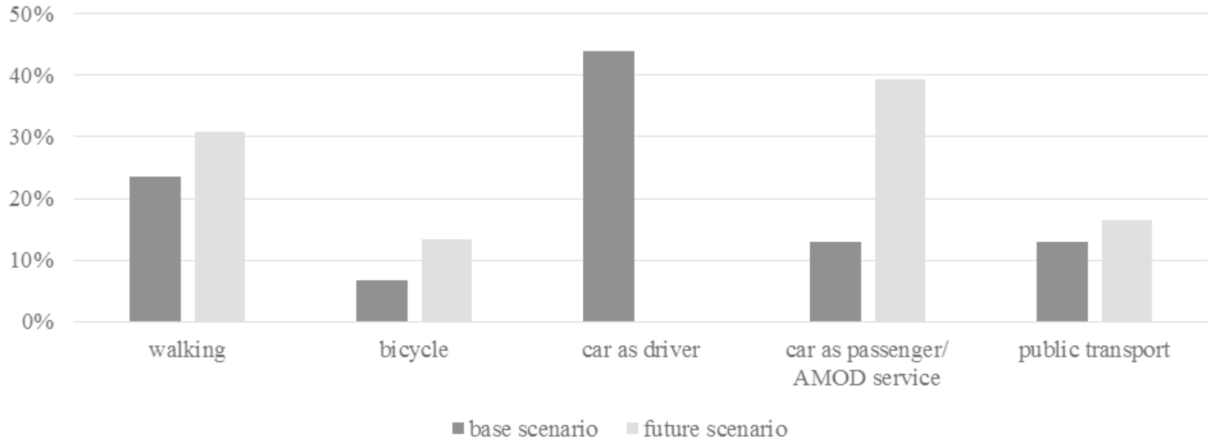

Fig. 1 Modal shift for the base and the future scenario: mean over one week

Further, short trips below two kilometers former made by car are substituted by the modes walking and/or cycling. Hence, the positive environmental effects are not just caused by the more effective AMOD system, but also by the mode substitution.

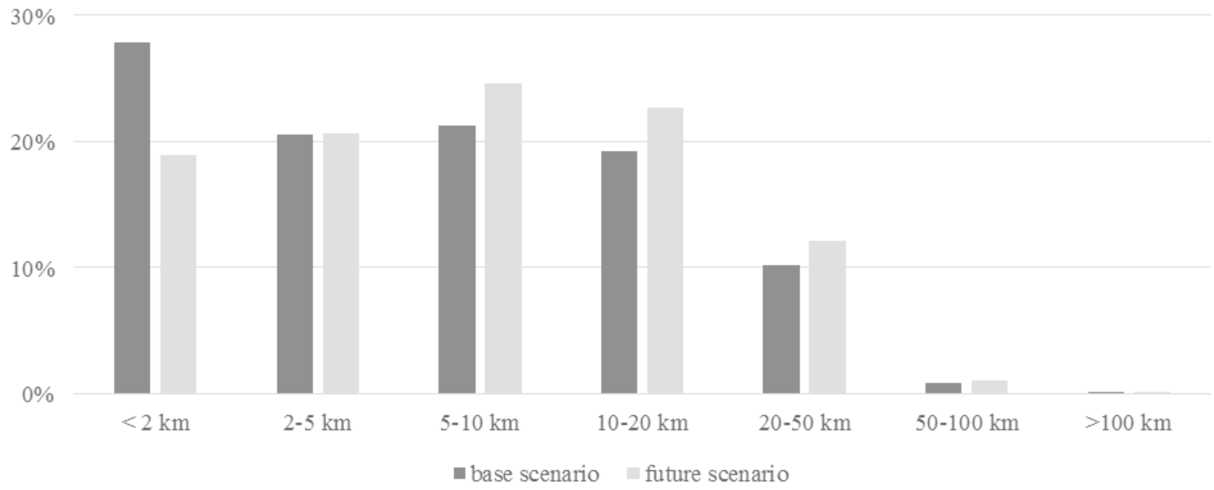

Fig. 2 Car trip distances for the base and the future scenario: mean over one week

5.2. Results of Step 2: AMOD services – Vehicle trips and kilometers

Using the base scenario of *mobiTopp* for the Stuttgart Region, about 44% of all trips are made by car as driver. Table 1 shows the amount of vehicle trips before and after the carpooling measures (future scenario) and the corresponding kilometers travelled by these cars.

Table 1. Comparison of vehicles trips and kilometers – base scenario and future scenario

	Base scenario	**Future scenario**	**Saving potential**
Number of vehicle trips	22.679 mio.	12.340 mio.	46%
Kilometers travelled	191.352 mio.	152.625 mio.	20%

The amount of vehicle trips that can be saved is about 46% - almost the half of all vehicle trips - but only 20% of the kilometers travelled can be saved, also due to longer trips caused by the lower AMOD service costs (see 5.1). Hence, especially short trips are pooled in our scenario. Since there is a general majority of short car trips (below 10 kilometers), the number of zones that can be reached by these trips is limited. Consequently, these trips are more likely to be pooled because there is a higher likelihood for another trip with the same origin and destination within the same time slot. Longer trips have a higher range of possible destinations and are therefore harder to pool together.

5.3. Results of Step 2: AMOD services – Amount of vehicles needed

We further calculated the number of vehicles needed to fulfil the demand of autonomous vehicle rides. We allowed for vehicle relocations only during nighttime. This allows us to redistribute the vehicles to the zones where they are needed the next day.

Table 2. Key figures for nighttime relocation

	Number of vehicles needed	**Number of vehicle trips (without relocations)**	**Number of relocations trips during nighttime**
Monday	212,767	1,847,090	-
Tuesday	219,601	1,902,025	38,148
Wednesday	220,911	1,929,766	44,761
Thursday	218,128	1,955,778	42,016
Friday	198,290	1,968,399	35,038
Saturday	121,269	1,556,330	19,158
Sunday	103,519	1,180,848	21,960
Mean	184,926	1,762,891	28,726

Table 2 shows that there are about 28,700 relocations in average needed every night to relocate the vehicles for the next day. The maximum of over-night vehicle relocations is reached in the night from Tuesday to Wednesday. Nearly 45,000 vehicles have to be relocated for getting a good start scenario for Wednesday morning. As the relocation process takes place during the night, it has nearly no impact on the traffic situation because the traffic loads are very low at that time.

In the future scenario, about 2 million car trips per day are caused by the AMOD service in the Stuttgart region. In the base scenario, about 3 million car trips are made. Under the given assumption that the maximum number of vehicles is needed to fulfil the inhabitants' travel demand at any time, about 221,000 AMOD vehicles are needed. The peak is on Wednesday, which is also the day with the most trips during the week. Today, there are around 1,565,000 private cars registered in the Stuttgart region. Consequently, only about 15% of the vehicles of today are needed to satisfy the car-travel demand. One can see that there is a high potential of reducing the number of vehicles. Additionally, if the number of cars will be reduced, there is a lot of more space in the streets due to less car parking.

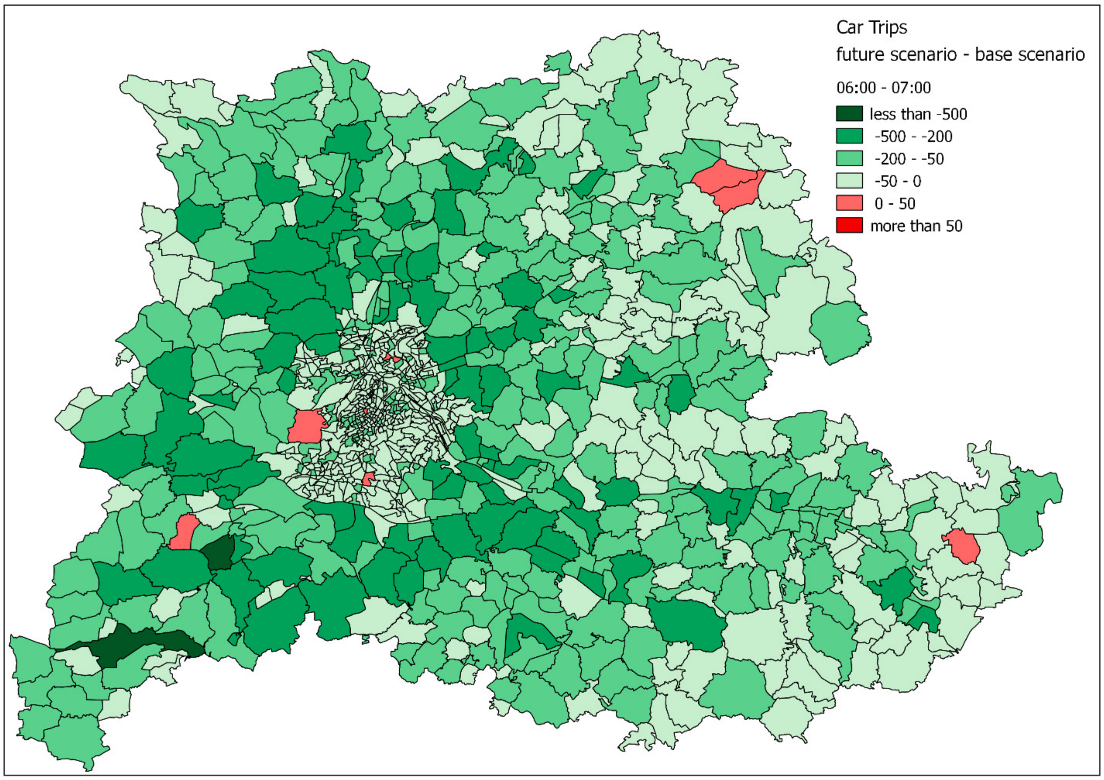

Fig. 3 Difference of originating car trips on a weekday-peak hour: Future Scenario – Base Scenario

A reduction in total trips does not necessarily result in less trips everywhere. In order to assess the peak load of the road infrastructure, we analyzed the morning peak hour on a regular weekday.

Fig. 3 shows a comparison of both scenarios for originating car trips in a spatial distribution. Zones with more originating car trips caused by the AMOD service in the future scenario are marked red, whereas zones with less originating car trips in the future scenario are marked green. The red cells are mainly concentrated in the city center of Stuttgart as well as in areas with a poorer public transportation service.

Especially in the city center, the accumulation of red areas indicates that there will be more cars on the streets in some areas. Hence, one can assume more congestion and higher travel times in those areas. To prove this assumption though, a traffic assignment would be a necessary and suitable method.

6. Conclusion and further research

In this paper, we calculated the effects of an AMOD service with no private owned vehicles. Only autonomous vehicles are used to serve the populations' car-travel demand. Therefore, we use the multi-agent travel demand model *mobiTopp* for the Stuttgart region. We created a future scenario with the modes car as passenger (of an autonomous vehicle), public transport, bicycling and walking. The mode car as driver was disabled. We further assumed that all trips of the same O-D pair based on zones can be pooled with other users desiring the same O-D-relation. Our approach hence considered on the one hand the modal shift between the different modes and on the other hand the possibility of pooling trips with the same O-D-relation.

As expected, the AMOD service reaches a high share of the modal split; the share of all other modes increases as well. Due to the restriction, that the mode car as driver is not available anymore, one would assume that it is mainly substituted by the AMOD service. However, the modal share of walking, public transportation and bicycling is increasing as well. Due to the lower cost of the AMOD service compared to car trips, the trip length in general increased. In the future scenario, about 45% of all trips and 20% of all vehicle kilometers can be saved. Furthermore, about 85% off all vehicles in the Stuttgart region might be dispensable, considering only a relocation of the vehicles during the night.

However, the vehicle usage regarding spatial effects has to be analyzed further. Especially traffic assignment could show local concentrations in the usage of the AMOD services. As a consequence, the traffic assignment can, of course, just be seen as accurate, if the resulting travel time matrices serve again as input for the travel demand model and the whole process is looped. In order to optimize the AMOD service, also the relocation has to be modeled in more detail.

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