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## Simulation of automated transport offers for the city of Brunswick

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### Abstract

The introduction of automated vehicles in the transport system is widely expected to have significant impact on traffic flow and safety, mobility behavior, car ownership and modal usage. Not only the replacement of conventional passenger cars by automated ones but also other forms of mobility offers are being discussed, such as the introduction of vehicle-on-demand fleets. When investigating the effects of such systems, the changes in the perceived travel time have to be regarded. Within this paper, the effects of introducing automated vehicles as well as vehicle-on-demand and shared vehicle-on-demand offers are presented. Eight different simulation settings with different fleet sizes and shares of private automated vehicles were evaluated using an agent-based demand model. The factors for value of time were obtained from a stated preference user survey. The results show only minor changes in the modal split and the amount of rides for the city of Brunswick due to the relatively small travel distances prevailing.

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*Keywords:* agent-based demand modelling; automated vehicles; vehicle on demand; simulation

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### 1. Introduction

Automated vehicles are assumed to have an enormous impact on transport and mobility<sup>1,2</sup>. The magnitude of the effects of their introduction on traffic flow and safety as well as on individual mobility behavior, car ownership and mode choice are yet highly uncertain and often analyzed using simulations<sup>3,4,5</sup>. These evaluations discuss a broad variety of mobility offers based on automated vehicles, among them replacing conventional public transport busses,

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vehicle-on-demand fleets, shared vehicles or automated passenger vehicles owned by individuals. Consequently, many different approaches for simulating automated vehicles as well as a large number of scenarios exist.

Scenarios usually share an optimistic view on the extent of changes expected by the introduction of AVs. Often, major changes in mobility behavior and subsequently in the road usage are assumed. Scenarios evaluating the effects of vehicle-on-demand (VOD) fleets and shared VOD usually put the main focus on the prospective reduction of the overall vehicle fleet and the resulting parking place savings. Within such investigations, usually a given, simulated demand is used and rides performed using conventional passenger cars are replaced by automated vehicles and a disposition algorithm that moves the vehicles to the next location for picking up the subsequent passenger is presented<sup>6,7,8</sup>. The main goal is to develop algorithms that reduce the amount of needed vehicles and/or the driven kilometers<sup>7</sup>. While in most cases, such shared automated offers are shown to reduce the overall traffic, the disposition of automated vehicles can as well induce additional traffic and yield in a worse situation on the roads<sup>8,9</sup>.

In the following, the results of simulating automated offers, including automated passenger cars, vehicle-on-demand (VOD), and shared VOD offers are presented. Hereby, the focus is put on changes in the perception of travel time, known as value-of-time (VOT), and the resulting effects on mode choice and on using (automated) passenger cars. Travel demand is calculated from the scratch, determining the behavioral changes after introducing automated vehicles based on VOT changes derived from a stated preference survey on mode choice<sup>10</sup>. The simulated automated vehicles are assumed to be fully automated, yet no relocation is modelled for the VOD fleets.

The remainder is structured as following. In Section 2, the simulation system is described. Section 3 presents the simulation scenario. The results of the simulation runs are given in Section 4, followed by a discussion in Section 5.

## 2. Simulation System

The effects of introducing automated vehicles were computed using the agent-based passenger transport demand model TAPAS<sup>11,12</sup>. Within a TAPAS simulation, a region is described mainly by a population consisting of single individuals, the activity places within the region, as well as travel time and cost matrices which describe the performance of available modes of transport. TAPAS processes the modeled population by iterating over households and then over the respective household's members. For each of these persons, the activity places to visit over the day and the modes used to access them are computed. TAPAS supports different location and mode choice models. For the investigations described herein, an intervening opportunities model was used for location choice and a multinomial logit (MNL) model for selecting the transport mode to use.

For simulating the impact of automation, three enhancements of the existing model had to be implemented: a) the differentiation of privately owned vehicles by the existence of automation functions, b) the differentiation of travel times and VOTs depending on the automation of the vehicle in the mode choice and c) the integration of VOD and shared VOD as mode choice alternatives.

Assumptions for deriving the penetration rate of the privately owned vehicle fleet with automation are presented in the following section. For adopting VOT and travel times, the results of a stated preference (SP) study was used. For a given current and an anticipated future situation, a SP-experiment was conducted and used to estimate multinomial logit models for mode choice and to derive VOT estimates. Kolarova et al. 2017<sup>10</sup> and Steck et al. 2018<sup>13</sup> give detailed insight on the survey methodology, sample and model estimation. There are different possibilities to embed the likeliness to use an automated vehicle within a demand model. The first one is to directly utilize the mode choice estimates for the future situation. The other one, used herein, is to apply the changes of the estimated value-of-time (VOT) in the existing mode choice model as soon as an automated vehicle is available. Changes in VOT between the current and future situation were determined using public transport values of the mentioned SP-survey as reference. Hereby, current VOT-values for manually driven passenger cars ( $VOT_{normal}$ ) and the public transport ( $VOT_{PT1}$ ) were contrasted with the VOTs of automated vehicles ( $VOT_{autonom}$ ) and public transport ( $VOT_{PT2}$ ) for the future situation. The respectively used values are given in Table 1. The corresponding factor  $c$  for the changes in VOT was differentiated by two distance categories, one for rides with a distance below 10km and one for those with more than 10km and computed as  $c = b/a$ . As can be seen, VOT for automated vehicles was estimated to be roughly at the 89% level of conventional cars for shorter and a little lower for longer trips, what reflects the anticipated advantages of alternative time use on longer trips.

Table 1. Value-of-time values obtained from the surveys and resulting anticipated benefits of using automated vehicles

	$VOT_{normal}^*$	$VOT_{PT1}^*$	$VOT_{autonom}^*$	$VOT_{PT2}^*$	$c$
$\leq 10\text{km}$	8.03€/h	8.46€/h	3.52€/h	4.28€/h	0.87
$> 10\text{km}$	10.44€/h	8.42€/h	4.82€/h	4.9€/h	0.79

In addition, it was assumed that the advantages of riding in an automated vehicle only applied after a ramp-up time, so that changes in VOT were only considered for trips with a duration of more than 5min. The approach of the non-modified ramp-up time was chosen to reflect the time needed for getting settled in the car, e.g. for getting a book or an electronic device ready to use, and to pack up at the end of the drive. The trip duration is used as a coefficient of the MNL mode choice model. For automated vehicles, a new weighting function (see Formula 1) for the anticipated distance was used. Summarizing, travel times used in the TAPAS' mode choice procedure were adopted as sketched when the private car was supposed to be automated:

$$t_{automated} = \begin{cases} t_{conventional} & | t_{conventional} \leq 5\text{minutes} \\ 5\text{minutes} + c_{dist} \cdot (t_{conventional} - 5\text{minutes}) & | t_{conventional} > 5\text{minutes} \end{cases} \quad (1)$$

The second needed extension was the introduction of vehicle-on-demand (VOD) offers, also known as automated car sharing, in the mode choice module of the demand model. The basic change was the introduction of a new transport mode, for which the parameter estimates for travel time, costs, and trip purpose were adopted from a conventional passenger car, yet with adapted values for the age distribution and for the mode constant<sup>11</sup>. Despite the fully automated driving function, it was assumed that users of VOD must have a driving license, following current policies for the usage of car sharing vehicles.

Additionally, the introduction of shared usage of VOD services was assumed for some of the scenarios. Because no empirical information about the willingness to share such offers exists, a simplified approach was taken, assuming that all VOD trips can and will be shared. It was further assumed that a shared usage reduces the price by half in comparison with a conventional VOD, while the waiting time for the service was increased from 3 to 5 minutes due to additional stops and detours.

### 3. Simulation Scenarios

The simulated area consists of the middle-sized city of Brunswick, Germany. Albeit being modelled, the usage of automated offers in the area surrounding the city as well as commuting trips to the city is not considered in the following. The set of simulations includes base cases for the year 2010 and 2030 without automated vehicles and further scenarios based on the 2030 base case where different automated vehicle offers are introduced.

#### 3.1. Base cases for the Brunswick region

For the base year 2010, the population for the city was derived from the commercial NEXIGA data describing population attributes at the level of residential districts for 2012. Using the SYNTHESIZER<sup>15</sup>, a tool for the generation of synthetic populations, these numbers were adapted to the German Mikrozensus 2010 (micro census), and completed with further person and household related attributes needed by the simulation. Different data sources such as employments statistics and regression models estimated on basis of mobility behavioral data such as the survey "Mobilität in Deutschland"<sup>14</sup> were used for this purpose. Attributes comprise professional status, availability of driving licenses, public transport passes and the number and type of cars in the household.

Assumptions about the population development until the year 2030 followed the census-based Raumordnungsprognose published by the "Bundesinstitut für Bau-, Stadt- und Raumforschung" (BBSR) and is consistent with the development assumed in the official German traffic prognosis (VP2030). As shown in Figure 1, the overall population for 2030 is slightly lower than the one for 2010, and a shift in age groups can be observed. Also, one can find a tendency towards smaller household sizes yielding in a larger number of households in 2030. Overall, the spatial distribution of the population remains almost the same.

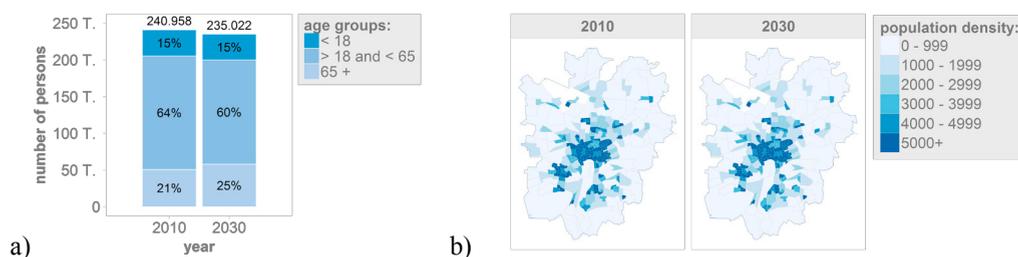


Fig. 1. a) Size and age constitution of Brunswick population for the years 2010 and 2030; b) population density within the simulated area.

The prices for using vehicles were set according to Table 2, following the price forecasts developed for the project “Renewability 3”<sup>16</sup> in accordance with the VP2030.

Table 2. Energy prices per kilometer used within the scenarios.

Fuel / transport type	Costs in Eurocent	Changes in comparison to 2010
Gasoline	13.3	+14.7%
Diesel	9.6	+10.3%
Gas	6.8	+23.6%
Plugin-Hybrid	9.0	-14.3%
Fully Electric	7.4	-29.5%
Public transport	11.23	+21.0%
Vehicle-on-demand (VOD)	60	N/A
Shared vehicle-on-demand (Shared VOD)	30	N/A

### 3.2. Automated offers scenarios

For computing the effects of automated vehicle offers on mobility and traffic, eight simulation settings with different offers and fleets have been set up. First, the replications of the base cases for the year 2010 (“base 2010”) and 2030 (“base 2030”) with no automated vehicles were implemented. The third simulation setting (“PVA”) assumes the introduction of privately owned automated vehicles. Here, 44% of the vehicle fleet was defined as offering fully automated driving functions, following a scenario developed in the IFMO project<sup>1</sup> with a rather optimistic penetration rate. Furthermore, three simulations that include privately used VODs were set up. The first one (“VOD\_const”) contains the original vehicle fleet and only the VOD vehicles run automatically. Within the second one (“VOD\_red”), the vehicle fleet was reduced, assuming a lower car ownership due to the availability of shared vehicle offers. The third one (“combi\_VOD\_red”) combines private automated vehicles with a reduction in car ownership and a fleet of VOD vehicles. In addition, two simulation settings that introduce shared usage of automated vehicle-on-demand offers were implemented. The first one (“VOD\_shared\_red”) combines the availability of shared VOD with a reduced fleet size. The second one (“combi\_VOD\_shared\_red”) assumes the presence of both, shared and individually used VOD and automated private vehicles with a reduced fleet size. Table 3 gives a summary of the implemented simulation settings.

Table 3. Implemented simulation scenarios.

Name	Share of automated vehicles	VOD (availability, fleet reduction)	Shared VOD
base 2010 (base 10)	0%	N/A	N/A
base 2030 (base 30)	0%	N/A	N/A
44% private fully automated vehicles in 2030 (PVA)	44%	N/A	N/A

VOD with base vehicle fleet ( <i>VOD_const</i> )	0%	city area; no fleet reduction	N/A
VOD with reduced vehicle fleet ( <i>VOD_red</i> )	0%	city area; fleet reduction	N/A
VOD and Shared VOD with reduced fleet ( <i>VOD_shared_red</i> )	0%	city area; fleet reduction	yes
Private fully automated vehicles with VOD and a reduced vehicle fleet ( <i>combi_VOD_red</i> )	44%	city area; fleet reduction	N/A
Private fully automated vehicles with VOD and shared VOD and a reduced vehicle fleet ( <i>combi_VOD_shared_red</i> )	44%	city area; fleet reduction	yes

The degrees of automation were determined for the vehicle sizes small, medium, and large and applied to the vehicle fleet of the city of Brunswick. Due to the relatively large number of large vehicles within the city, the resulting degree of automation amounts to 47% when no fleet reduction is applied and 46% for the reduced fleet (see Table 4). Attachment of the vehicle fleet to households was based on the assumption that the primary vehicle would be replaced by an automated one first. Consequently, only 1% of a household's secondary vehicles are automated.

Table 4. Penetration rates of automated vehicles used for the scenarios.

Area	small	compact	middle	large	In sum
Germany	27%	45%	45%	57%	44%
City of Brunswick (no fleet changes)	27%		47%	56%	47%
City of Brunswick (fleet reduction)	26%		46%	56%	46%

#### 4. Results

Investigating as a first step the numbers and distributions of trips per purpose, it can be observed that the number of trips decreases from 2010 to 2030. Distribution of trip purposes remains almost constant, with a slight decrease of educational and work trips. Main drivers of this development are the increases in the population's age and in transport costs. When comparing the simulations for 2030 with different mobility offers, only minor differences in the distributions of trip purposes can be found. Small decreases of the overall number of trips can be identified for the scenarios incorporating a reduction of the private vehicle fleet (all “\*\_red” scenarios). Trip pattern choice and consequently starting time of trips also remain widely unchanged.

Changes in the anticipation of travel times of new travel modes may yield in a different choice of the mode to use. Thus, Figure 2a shows the mode shares obtained for the simulation runs, distinguishing between conventional and automated vehicles if applicable. Only small differences between those scenarios where the vehicle fleets have not been reduced can be observed. In parallel, a reduction in the use of cars to about 35% can be observed in the scenarios with a reduced fleet. The only slight decrease may be explained by the fact that a household's second vehicle is often abandoned first. Additionally, Figure 2b focusses on the mode choice of persons whose households do not own a vehicle. Obviously, the mode “driving an own car” disappears, and the usage of an own vehicle as a co-driver is lower than in the overall population.

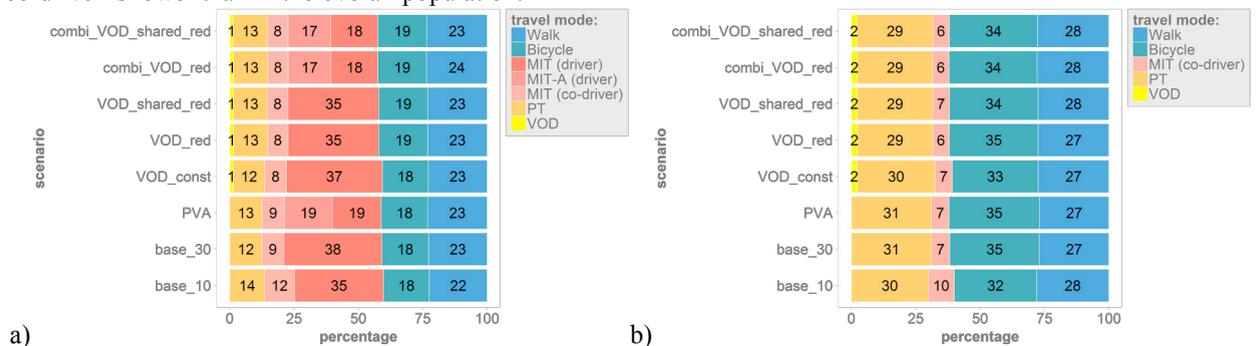


Fig. 2. Mode share distribution within the city of Brunswick for the scenarios, a) all inhabitants b) inhabitants without a car in the household

Over all scenarios, it is also remarkable that the amount of passenger trips performed with an automated vehicle reflects directly the share of these vehicles in the corresponding vehicle fleet. E.g., within the *PVA* scenario, about 50% of the trips performed by car are undertaken using an automated vehicle with their share being at 47% (see Table 4 and Figure 4a). As shown later, this goes along with longer trip distances for automated vehicles.

The share of using a vehicle as a passenger decreases from 11.6% to 8.6% between the base cases for the years 2010 and 2030, probably due to an increase in the motorization rate. An additional decrease can be observed for the simulation settings with a reduced vehicle fleet.

The availability of VOD reduces the share of public transport within the *VOD\_const* scenario. Though, the amount of trips undertaken by a VOD is in all regarded scenarios relatively low at about 1.4%. The additional inclusion of shared offers reduces the share even more, even though the number of owned vehicles was reduced. The reason is the increase in travel time when using shared VOD offers by two minutes that cannot be compensated by the lower costs. Regarding active modes of transport, a small increase between the 2010 and the 2030 base cases can be seen, as well as within the scenarios with a reduced vehicle fleet. Yet, using VOD still reduces the share of active modes.

For car-non-owners, the inclusion of automated offers has no major effects on the mode share, either. The shares of active modes are double or three times as high as for the whole population. Within the *PVA* scenario, one third of the trips are performed using active modes. Nonetheless, one can see that persons without an own vehicle use the new VOD offers more often than car owners. Within the scenarios *VOD\_red* and *combi\_VOD\_red*, the share of VOD is almost twice as high as for car owners. The low acceptance of shared VOD is again visible for car-non-owners, and the increase in VOD usage usually reduces bicycling.

It is often assumed that automation will lead to an increase in vehicle miles travelled. Figure 3 shows the travelled distances distinguishing them by mode. Overall, only minor changes can be observed. When comparing travelling distances between conventional and automated vehicles, one can see that the ones of automated vehicles are always higher. Here, the effect of the reduced VOT can be seen. Also, the reduction of the vehicle fleet is reflected in the increase of the distances travelled using public transport. Average trip length for VOD is rather short, even shorter than for bicyclists.

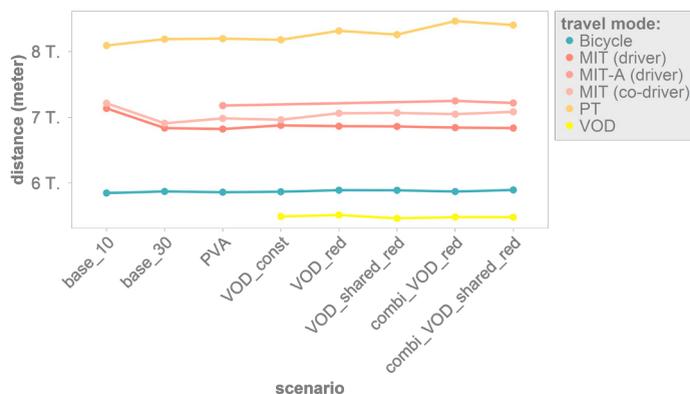


Fig. 3. Comparison of the average travel distances of different transport modes for the simulated settings.

Figure 4a shows the development of the person kilometers, travelled by privately owned car, distinguishing – where applicable – between conventional and automated vehicles. Only trips performed as a driver are counted, as for co-drivers this information is not available. All trips starting within the city of Brunswick are regarded, also those ending outside the city. Following an increase between 2010 and 2030, in all but the *PVA* scenario, the amount of vehicle kilometers declines over all simulation settings in comparison with the base case 2030.

The contribution of the assumed VOD offers to the person kilometers travelled is highlighted in Figure 4b. It shows that the reduction of the privately owned vehicle fleet goes along with a slight increase in usage and kilometers spent in VOD (see Figures 2 and 4b). Again, the lesser attraction of shared rides can be seen.

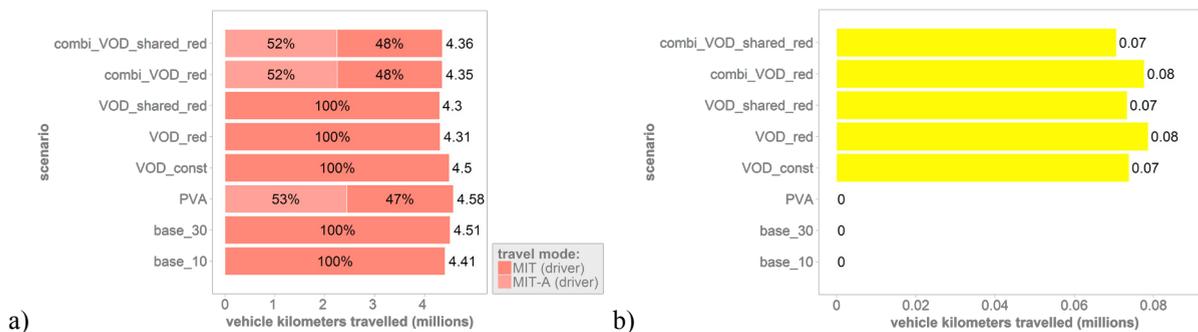


Fig. 4.a) Person kilometers travelled by car as driver; b) Person kilometers travelled of VOD vehicles.

### 5. Discussion

The paper presented the results of simulation runs envisioning the introduction of automated vehicles and (shared) vehicle-on-demand fleets in the city of Brunswick. The paper introduces the data base and assumptions used for the definition of simulation settings, gives details on the changes in the agent-based demand model TAPAS taken for implementing VOD offers and differentiation by automating degree of private cars, and presents the evaluation of the simulation runs.

Compared with most of the settings presented so far in the literature, effects on the mobility behavior and traffic in the city of Brunswick have to be considered rather small. The number of trips as well as their distribution over time change only slightly between the simulation runs, and changes can be mainly attributed to a decrease in car ownership. The scenario introducing automated vehicles without assuming a fleet reduction (scenario *PVA*) shows at the same time the commonly expected implications on travel behavior and traffic: a moderate increase in person kilometers travelled by car that can be attributed to the reduction of VOT implemented in the scenarios for automated vehicles. Also when looking at the scenarios assuming the prevalence of automated taxi services (VOD), utilization of this mobility services remains moderate even when assuming a reduced vehicle ownership at the same time. Furthermore, shared VOD services show – despite the lower cost but due to the assumed increase of travel time as consequence of detours and service waiting – a noticeably lower attractiveness than their individually used counter parts. In general, it can be seen that VOD mainly replace the usage of a bicycle and this predominantly for persons not owning a private car.

The introduction of automated private vehicles and VOD services implemented similar to the scenarios presented here can surely not be seen as game changer of urban transport within cities of a size similar to Brunswick. There are several aspects contributing to the limited impacts seen in the simulation runs. Partially, these might be attributed to the conservative usage requirements assumed, including a minimum age of 20 and the availability of a driver license. Other aspects contributing to the relatively low modal shares are surely the relatively good public transport provisions and the on-average short trip distances that can be seen in the city of Brunswick. But the major aspect is the small time benefit of using automated vehicles within the city due to the relatively small area and accordingly small distances. Figure 5a illustrates this by giving the distribution of trip lengths for automated and conventional vehicles performed as a driver. It shows that more than 60% of the trips are below 7km and therefore do not benefit of the lower value of time when riding an automated vehicle. Additionally, Figure 5b illustrates how the effective travel time, the perceived travel time, and the travel time savings change over the travelled distance assuming a velocity of 30km/h. One can easily recognize the ramp-up threshold of five minutes that has to be reached before the travel time is anticipated as being less annoying. Overall, travel time savings for more than 60% of the trips remain at minute-level and therefore contribute to the small changes seen above. The findings call for the extension of the analysis area, thus including a larger share of commuters in and out of the city as well as inhabitants of more rural areas in which the analyzed mobility services might be a good supplement for public transport and travel distances are generally longer. Significant differences in impact are expected here depending on spatial setting, public transport service and demographic situation.

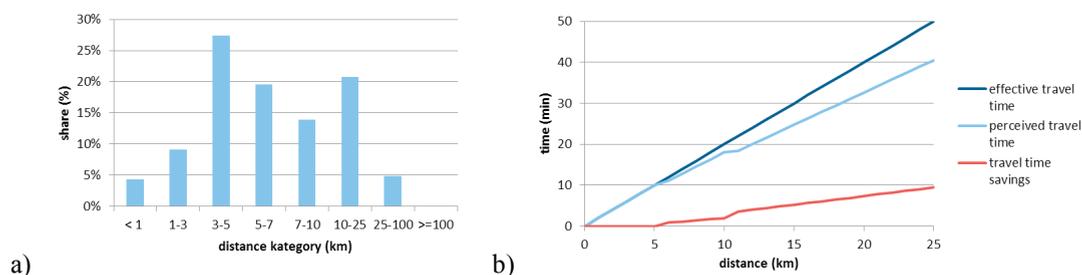


Fig. 5. a) Distribution of the distances travelled within the city of Brunswick in the *combi\_VOD\_shared\_red* scenario including conventional and automated vehicles. b) Real and perceived travel times and the resulting time savings in dependency to the travelled distance.

Further issues to be addressed are the assumptions taken for modelling the usage of VOD. Whereas the limitations of the VOD offers to users with an age of at least 20 years and a driving license are plausible, they do not reflect addressing new user groups that is often associated with the introduction of such offers. Future research will therefore analyze usage potential and behavioral implications of VOD services being accessible without restrictions and thus for e.g. children, elderly and mobility impaired persons. Finally, it should be pointed out that no disposition of VOD vehicles was modelled yet – yielding in neglecting empty trips – a shortcoming to be addressed.

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