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Autonomous Vehicles: The next Jump in Accessibilities?

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Abstract

Autonomous vehicles are expected to offer a higher comfort of traveling at lower prices and at the same time to increase road capacity - a pattern recalling the rise of the private car and later of motorway construction. Using the Swiss national transport model, this research simulates the impact of autonomous vehicles on accessibility of the Swiss municipalities. The results show that autonomous vehicles could cause another quantum leap in accessibility. Moreover, the spatial distribution of the accessibility impacts implies that autonomous vehicles favor urban sprawl and may render public transport superfluous except for dense urban areas.

Keywords: autonomous vehicles, self-driving vehicles, road capacity, user groups, induced demand, accessibility, land use, urban sprawl

JEL: R10, R41

1. Introduction

Fully autonomous vehicles (AV, NHTSA-Level 4 [1]) promise a fundamental revolution in mobility. They are expected to make traveling safer [2, 3, 4], cheaper [5], more comfortable, more sustainable [2, 6, 7, 8, 4], and thus to substantially reduce the generalized costs of travel. They will open car travel to children, elderly and the disabled [2, 9, 10, 6]. Depending on the sce-

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nario, they may also trigger a substantial reduction of the total vehicle fleet [11, 12, 13, 14, 15, 16, 17] and substantial road capacity gains [18, 19, 20, 21].

If all those assumptions are to become true, autonomous vehicles will not only revolutionize transportation, but dramatically change the urban form. By substantially reducing the generalized cost of travel, they may induce substantial amounts of additional travel demand [22, 23] and boost a new wave of suburbanization and urban sprawl [24]. This research is a first attempt to explore such impacts of autonomous vehicles at a large scale, here for Switzerland. By studying how autonomous vehicles change the accessibility levels [25] of the Swiss municipalities, it builds upon previous research [6, 26] by offering further insights on the shape of future AV-cities and the prospects of public transportation.

To date, only few attempts have been made to study the impact of autonomous vehicles on accessibilities. For example, Kim et al. [27] used an activity-based model to study the travel behavior impact of autonomous vehicles for the Atlanta, GA, region. Assuming a 50% increase in highway capacity, they observe an increase in accessibility for the entire Atlanta region including downtown Atlanta. However, the model only considers highways, which is a major limitation, because as shown by Friedrich [21], in an AV-regime, (non-arterial) roads where intersections determine the flow capacity may become major bottlenecks. Moreover, in many other studies highways are assumed to see even higher capacity increases than proposed by Kim et al. [27].

In a second approach, Childress et al. [28] used the Puget Sound activity-based transport model to study the impact of autonomous vehicles on the Seattle, WA, region, for four different scenarios. They assumed a 30% capacity increase on roads and 35% shorter perceived travel times when riding an autonomous vehicle. Moreover, they assumed a shared taxi scheme, however, operating at current taxi prices and therefore neglecting the substantial drop in operating costs due to self-driving technologies [5]. They observe substantial increases in travel demand (20%) for the scenarios with privately owned autonomous vehicles, but an even more extreme decrease (-35%) in travel demand for the scenario with a fleet of shared autonomous vehicles, which is probably due to the high prices assumed. For all scenarios, accessibility increases for the whole area including downtown Seattle, WA, were observed. Again, however, the assumed capacity increases likely are too low and were not differentiated between different street types. Moreover, assuming current taxi prices biases the resulting impacts for a shared autonomous vehicle scheme.

In addition, both studies neglect travel demand by new user groups and empty rides of autonomous vehicles. Yet, as indicated in earlier studies [2, 10, 6], these two factors account for a major share of the expected new demand. Therefore, it can be expected that including such effects in the analysis will yield different accessibility impacts.

One step into this direction has already been taken by Liu et al. [29], who addressed the problem from the perspective of mode shifts and empty rides. Using an agent-based simulation approach, they predict that if fleets of shared autonomous vehicles can be operated at relatively low prices, they will also attract a large number of former public transport users and generate a substantial amount of empty rides. However, they do not consider any changes in road capacities or additional travel demand generated by new user groups.

The research presented in this paper addresses these limitations by considering different levels of capacity increases, differentiating between street types and including additional travel due to new customer groups and empty rides.

2. Background

2.1. Autonomous Vehicles

Autonomous vehicles can drive without a human driver. However, different levels of autonomy can be differentiated [1]. This work assumes autonomous vehicles of NHTSA level 3 and 4 [1], i.e vehicles which can self-drive in some or all situations.

Fully autonomous vehicles have substantial direct impacts on road traffic. In the following, some impacts, which are important for the work presented in this paper, are introduced in more detail.

2.1.1. Capacity Impacts

One impact of autonomous vehicles are capacity gains on the road network. Based on traffic flow theory, Friedrich [21] suggests capacity gains of up to 80% on highways and of up to 40% on urban roads compared to today if all vehicles on the road were fully autonomous. In his estimates, increases in road capacity result from shorter reaction times of autonomous vehicles compared to humans. Yet, he still allows for a time gap to the next car, which is assumed to be acceptable for human passengers (0.5s), and he assumes the same basic design of vehicles as today. Neglecting those restrictions, Tientrakool et al. [18] suggest a capacity gain of up to 270% compared to today's highway capacity level. They assume a situation with 100% autonomous and fully-connected vehicles. Such capacity impacts can be seen as an optimistic, technically possible capacity gains. Other approaches by Brownell [20] or Fernandes and Nunes [19] suggest a capacity increase of up 80% for urban roads and 370% for highways as the technically possible upper limit. For this work however, these estimates are considered as too high as they require special driving maneuvers.

2.1.2. New User Groups

As autonomous vehicles do not require a driver, they provide car travel also for people who are not able or allowed to drive today [10, 6]. Considered in this work are elderly, children and adults without a drivers license, because they represent the largest groups of additional users.

2.1.3. Modal Shift

Shared autonomous vehicles can provide the door to door, individual travel experience of private cars at low prices and without the financial burden and hassles of private car ownership (sunk capital, taxes, insurances, repairs) [30]. In addition, they allow passengers to perform non-driving activities during the ride. Comfort-wise, this makes traveling with shared autonomous vehicles very competitive if not superior to today's forms of both conventional car ownership and public transportation. Thus, a substantial modal shift towards such new services can be expected.

2.2. Accessibility

Accessibility describes for a place, how well it is connected to opportunities such as work places, leisure and shopping opportunities. It is a key indicator of the social and economic attractiveness of a place, influencing its future development. Accessibility was first proposed by Hansen [25] as a concept for describing the quality of transport services in an area.

More formally, accessibility A_i of a place i is defined as the sum of all available social and economic opportunities X_j weighted by the generalized cost c_{ij} of reaching them. Different weighting functions $f(c_{ij})$ can be used, for example to differentiate the accessibilities of different modes. Often, the generalized cost of travel is simplified to travel time alone.

$$A_i = \sum_{c_{ij}} X_j \cdot f(c_{ij})$$

As travel costs are usually independent of the travel direction (A to B costs the same as B to A), the accessibility of a place also describes how well this place can be reached from any other place. In this sense, accessibility also describes the economic value and prospects of a place.

Based on the New Economic Geography [31], Duranton and Puga [32] propose three ways, in which higher accessibility leads to increases in productivity: It minimizes mismatch on the job market and therefore allows a higher degree of specialization; it allows to share the investments for example in universities or infrastructure among more beneficiaries; and it provides a higher number of peers or early adopters for any new idea, thus increasing creativity and the probability of new products to succeed.

Moreover, Weis [33] has shown that historically, changes in accessibility cause induced demand as people and businesses make use of those new opportunities. His results will be used in this research to obtain a first estimate of the induced demand to be expected due to autonomous vehicles.

In this research, accessibility is calculated based on the travel times in the assigned network of the Swiss National Transport Model after the demand has been assigned to the network. As a proxy for opportunities, work places have been chosen under the assumption that access to work places is a key determinant for economic and population growth. As weighting function

$$f(c_{ij}) = e^{-\beta \tau_{ij}}$$

has been used, given that this functional form is the most closely related to behavioral theory [34]. In the formula, the β parameter is a measure for the acceptability of travel times towards a given activity. It varies by mode and over time. Axhausen et al. [35] have estimated the parameter as $\beta = 0.2613$ for car travel in Switzerland for the year 2010. Given that this is the latest estimate for the β parameter in Switzerland, it is also used in this research. The second variable, τ, describes the car travel time between the two zones in question after assignment. Other contributions to the generalized cost such as price and comfort have been neglected in the calculation of accessibilities, since their future levels are unclear at this time for both autonomous vehicles and public transportation.

2.3. Swiss National Transport Model

In this research, the year 2030 forecasts of the official national transport model of Switzerland [36] are used. The national transport model is a macroscopic transport model with 3 114 traffic analysis zones spanning the whole country and its immediate surroundings. The travel demand is extrapolated based on the 2005 travel demand model and official projections for population size and economic growth by the Swiss Federal Statistical Office [37]. The model includes separate demand segments for public transportation, cars and freight. However, they are represented in two separate sub-models; one for individual traffic (i.e. cars and trucks) and one for public transportation and rail cargo. Throughout this research, it was assumed, that public transportation services and travel times remain unaffected by autonomous vehicles. Hence, only the sub-model for individual transport was used in this research.

Yet, the model neglects intra-zonal and intra-urban demand. The network contains the 2005 transportation network to which all infrastructure projects with approved funding (by 2005) were added.

The transport model provides three temporal states: morning peak hour, workday average and evening peak hour. Since in Switzerland, the evening peak (5pm to 6pm) is more extreme [38], it is considered the relevant state, which actually determines long-term decisions such as housing choice.

2.4. Volume-Delay Function

The impacts of autonomous vehicles are represented in the transport model as relative changes in demand as well as relative changes in capacities. Capacities are linked to travel times at a given load by a volume-delay function. Typically, in such volume delay functions, the actual travel time remains close to the free-flow travel time as long as the load of a given link is substantially below the capacity limit. Only when the traffic load approaches the capacity limit, the travel time increases. Depending on the function used, the travel time skyrockets (i.e. congestion occurs) at the capacity limit [39] or after [40].

Several different forms of volume delay functions have been proposed. The most commonly used today is the function proposed by the Bureau of Public Roads (BPR) [40], which is also used in the Swiss National transport model [36]:

$$t_{cur} = t_0 \cdot \left(1 + \alpha \cdot \left(\frac{q}{q_{max}}\right)^{\beta}\right)$$

where q is the load on the link and q_{max} is the link's capacity and α, β road-type specific parameters. It should be noted that the BPR function is only valid for homogeneous flow and can therefore not be applied to mixed traffic with both autonomous and conventional vehicles. Also, it is not clear yet, whether the BPR function also holds for autonomous vehicles. Given the lack of a more appropriate alternative, it is used in this research nevertheless.

2.5. Switzerland

For an easier interpretation of the results, Figure 1 shows the population densities of the Swiss municipalities. As can be seen on the map, Switzerland's 41 277 km^2 (about twice the size of New Jersey) are geographically divided into to three regions: The Jura, the Mittelland and the Alps. The Mittelland is a fertile plateau spanning from Geneva via Bern and Zurich to St.Gallen. It is embedded between two mountain ranges: the Jura to its north-west and the Alps to its south-east. The Mittelland covers 30% of the country's area, but hosts more than two thirds of the 8.3 million population (about the size of New Jersey) and the major share of the country's economic activity. Compared to the Jura and the Alps, it has an even denser private and public transport network. In turn, the Jura and the Alps, due to their rugged landscape, have a substantially lower population density, which mostly lives from agriculture,

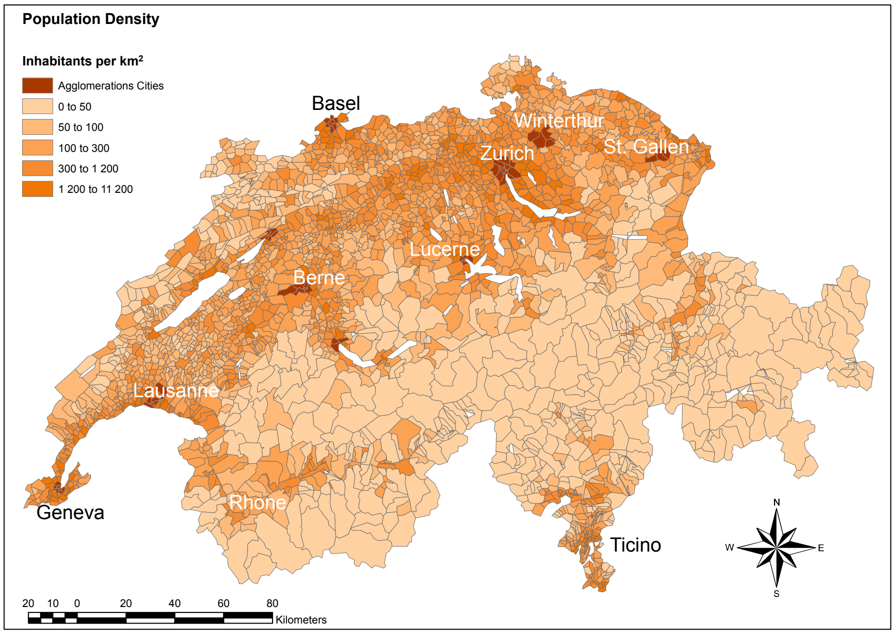

Figure 1: Population Density in Switzerland [36]

tourism, and/or specialized manufacturing (e.g. watches). Only at the descents to the Mittelland (especially Basel), in the Rhone valley or in the Canton of Ticino there is higher population density and considerable other economic activity. Switzerland's GDP reaches 482.3 billion USD (at purchasing power parity, comparable to New Jersey). Its population is expected to rise to 9.5 million in 2030 [36, 41, 42].

3. Methodology

Given that many aspects of future AV-based transport systems are still unclear, a scenario-based approach has been chosen to reflect the range of expected capacity impacts as well as different levels of additional demand.

As presented in the following, three main scenarios representing generic implementations of autonomous vehicles were defined. They were then tested for different capacity impacts and demand levels. Whilst the capacity impacts were included in the national transport model [36] by updating the link capacities in the network, the new demand levels were incorporated in the origin-destination matrix for cars.

Using the adjusted model, a new traffic assignment was performed for each scenario. Based on the resulting travel times, accessibility scores were then calculated for each municipality. The results of the different scenarios are then compared to the base case, which is the 2030 forecast of the transport model without any alterations due to autonomous vehicles.

Eventually, for the third scenario, a method proposed by Weis et al. [43] has been used to calculate the induced demand due to higher accessibilities. This way, the model can account for new trips or activities arising due to changes in the generalized cost of travel.

4. Scenarios

As described above, a scenario-based approach has been chosen, which covers the most likely and relevant aspects of future autonomous-mobility-based transport systems. In total, three scenarios are considered:

- Scenario 1, in which the advantages of autonomous vehicles can only be realized in extra-urban situations.
- Scenario 2, in which vehicles can operate fully autonomously in every situation, i.e. even within cities. However, vehicles remain in private possession and use.
- Scenario 3, in which vehicles can operate fully autonomously in every situation and a vehicle-sharing scheme is in place.

For all three scenarios, the capacity impacts estimated by Friedrich [21] (around 80% extra-urban capacity increase and 40% intra-urban capacity increase) are used as lower limits, while the capacity impact proposed by Tientrakool et al. [18] (270% extra-urban) serves as upper bound (also in this case, a capacity increase of 40% is assumed for urban roads).

Since the national transport model disregards capacities at junctions, only the road capacities were adjusted accordingly. By doing so, it was assumed, that the capacity estimates are valid for mixed traffic with cars, trucks and slow modes. Moreover, the demand for freight traffic (trucks) was assumed constant throughout all scenarios. The BPR function was applicable, because on the link level, only homogeneous situations with either purely autonomous or purely conventional traffic are considered in the scenarios.

4.1. Scenario 1

4.1.1. Description

The first scenario is a likely transition scenario towards a fully-autonomous transportation system. In this scenario, vehicles can drive autonomously on highways and extra-urban roads, but not within settlements. Therefore, a licensed driver is still required. Since the attractiveness of cars in such a scenario is only marginally higher than today, no changes in travel demand are assumed.

4.1.2. Results

The changes in accessibility are presented in Figure 2. For both the conservative and the optimistic capacity impact, substantial increases in accessibility are suggested for all regions throughout the country. Only two municipalities report a marginal decrease in accessibility, likely due to numerical noise in the assignment procedure. When weighted by population, the average gain in accessibility is 10% for the conservative and 14% for the optimistic capacity scenario. Municipalities with low increases are mostly situated in remote alpine areas.

4.2. Scenario 2

4.2.1. Description

The second scenario goes one step further by assuming full autonomy, i.e. vehicles can self-drive in all situations, even within cities. This unlocks new user groups for car-travel, most importantly children and elderly. Moreover, vehicles may travel empty to pick up passengers or goods or to transfer between two tasks.

Yet, in this scenario, only private ownership and use of all vehicles is assumed. However, vehicles may be shared within a household or family.

It is further assumed that adults between 18 and 65 years without a driver's license do not change their travel behaviour. The reason is, that only private ownership of a car is considered in this scenario. Since buying a car usually represents a much larger investment than obtaining a driver's license, it is assumed that automobility is not worthwhile for non-license-holders. Therefore, they would also not buy an autonomous vehicle.

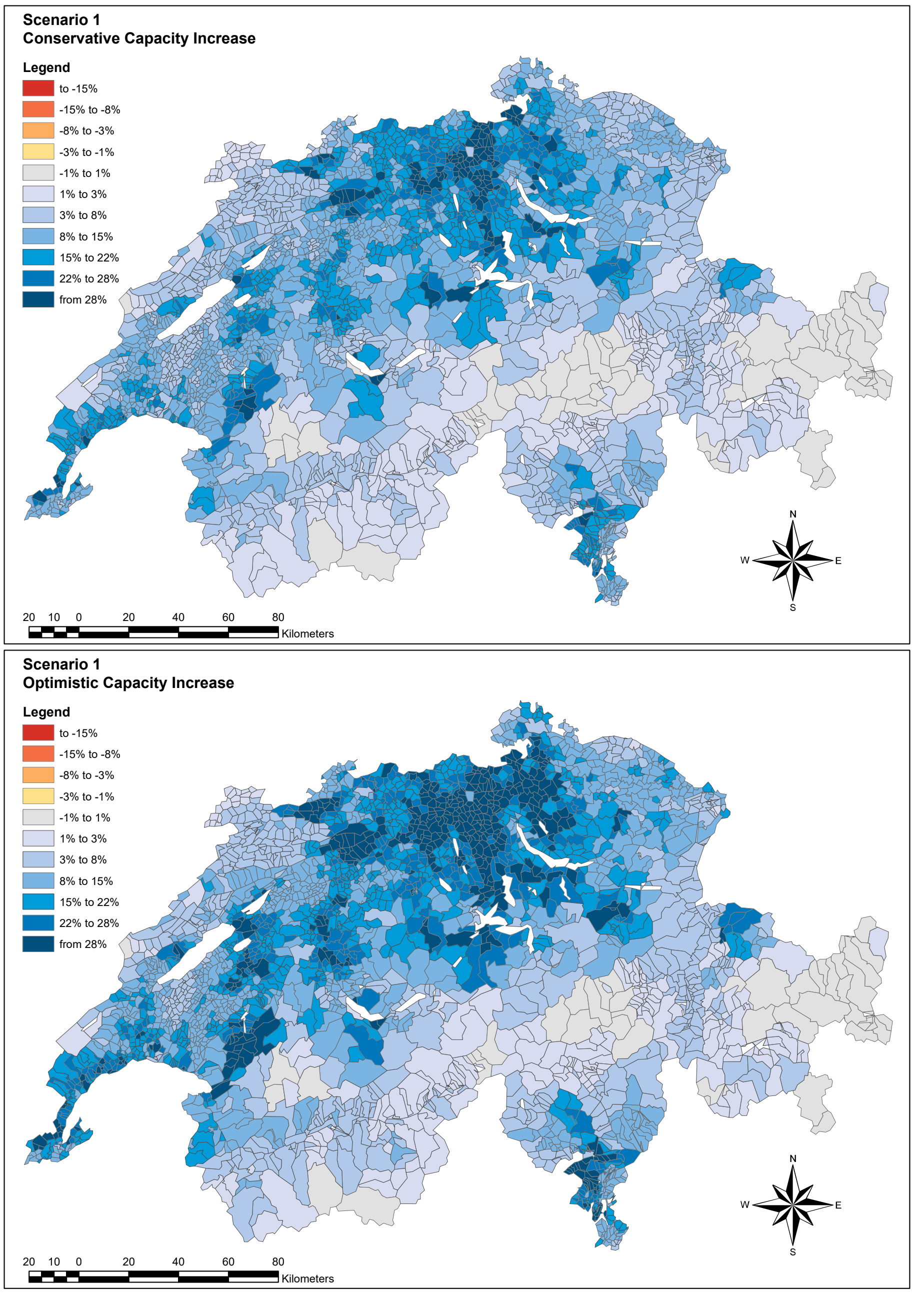

Figure 2: Relative changes in accessibility - scenario 1 [36]

Thus, in this scenario, new car travel demand is generated in two ways: First, by children and elderly substituting other modes by the family's private autonomous car and second, by private autonomous vehicles travelling empty. In the following, the magnitudes of the two effects are estimated.

Since no estimates for the new travel demand arising from these new user groups are available so far, the additional demand has been appraised using results from the Swiss transportation microcensus 2010 [38]. In a first step, it has been assumed, that the new demand arises from modal shifts from other modes. To estimate the magnitude of this effect, the distances the respective age groups travel by public transportation have been taken from the Swiss microcensus [38]. It was assumed, that the respective age groups shift all of their travel towards autonomous vehicles. Moreover, it was assumed, that each of the members of these age groups has access to a private vehicle. Thus, the scenario describes a maximum-impact case.

As shown in Table 1, the new customer groups (minors and seniors) travel a total of 234 749 km per day using modes other than car ($d_{MZ,new}$). Assuming they would change all this travel towards the car mode, this would represent a 16% increase in the total distance travelled by car by all age groups $d_{MZ,car}$, which translates into a 16% increase in the total car demand. The demand matrix has thus been updated using

$$D'_{i,j} = D_{i,j} \cdot \frac{d_{MZ,car} + d_{MZ,new}}{d_{MZ,car}} \qquad \forall i, j$$

with $D'_{i,j}$ being the updated travel demand for a given origin-destination pair (i, j), $d_{MZ,car}$ being the total distance travelled by car in the microcensus [38] and $d_{MZ,new}$ being the total distance of the assumed new car demand. This procedure presumes, that the relative modal shift is uniformly distributed around the country and throughout the day. Although this assumption surely is too strong, the expected bias is quite small. Moreover, most of the trips

Table 1: Mode use by age group based on data from the Swiss microcensus 2010 [38]

	<18 years	65-79 years	>80 years	all ages
mode	daily km	daily km	daily km	daily km
car	11.84	15.99	6.97	23.84
motorbike	0.55	0.15	0.01	0.51
active modes (walk, bike)	3.24	2.67	1.50	2.82
rail	4.63	4.96	3.55	7.06
regional bus	0.20	0.13	0.13	0.13
local bus	1.90	0.74	0.55	1.03
tram	0.26	0.30	0.26	0.37
taxi	0.04	0.01	0.05	0.04
rest	0.89	0.84	0.52	0.85
average car distance				23.84
average non-car distance	11.71	9.80	6.58	
N	7 808	12 017	3 883	62 868
total non-car distance $d_{MZ,new}$	91 432	117 767	25 550	
total car distance $d_{MZ,car}$				1 498 773

children and elderly usually perform happen outside of the evening peak hour. Therefore, adding their day-average to the peak hour demand can be regarded as an upper bound of the actual effect. Furthermore, the estimation of additional demand disregards that not every child or senior may have access to a vehicle in his family which can be regarded as another upward adjustment.

In addition to attracting new user groups, autonomous vehicles will also travel empty for various reasons. Since the extent of such empty rides depends on the actual pricing structures and regulations, three levels of empty rides have been assumed: 0.5, 1.0 and 1.5 empty rides per person per day. Given that a Swiss person undertakes an average of 2.86 car-trips per day [38], this implies an increase of up to 53%. Such empty rides include reposition trips of a vehicle between household members, empty travel when the vehicle is used as a mobility service robot (e.g. to pick up groceries bought online), and - at the more extreme end of the spectrum - empty return travel to the trip origin if no (free) parking space is available at the destination. Again, lacking any better estimates, it is assumed that the empty rides follow the spatial distribution of the original travel demand. Therefore, the demand matrix is updated using

$$D''_{i,j} = D'_{i,j} \cdot \left(1 + \frac{\alpha}{2.86}\right) \qquad \alpha \in \{0.5, 1.0, 1.5\} \qquad \forall i, j.$$

4.2.2. Results

In the following, the results are presented for the most extreme case with travel demand increased by 16% due to new user groups and by an another 53% due to empty rides. For some municipalities (i.e. cities), this means that the demand increases more strongly than road capacities. Hence, as shown in Figure 3, the additional travel demand reduces the gains in accessibility. Whilst in the conservative scenario, only minor gains in accessibility (with respect to the base case) are observed for the rural areas in northern and western Switzerland, losses in accessibility occur for the larger agglomerations such as Geneva, Lausanne, Basel, Zurich and St. Gallen. This way, the population-weighted average increase in accessibility drops to almost zero.

In contrast, the map for the optimistic scenario shows substantial increases in accessibility throughout the country with only few exceptions (2% of the municipalities), in which a negative impact on accessibility is predicted. In population-weighted average, accessibility increases by 10%.

4.3. Scenario 3

4.3.1. Description

The third scenario assumes a future, in which there is a fleet of shared autonomous vehicles available for everybody. In turn, there is no private vehicle ownership anymore. It is assumed that travelers are picked up at their origin

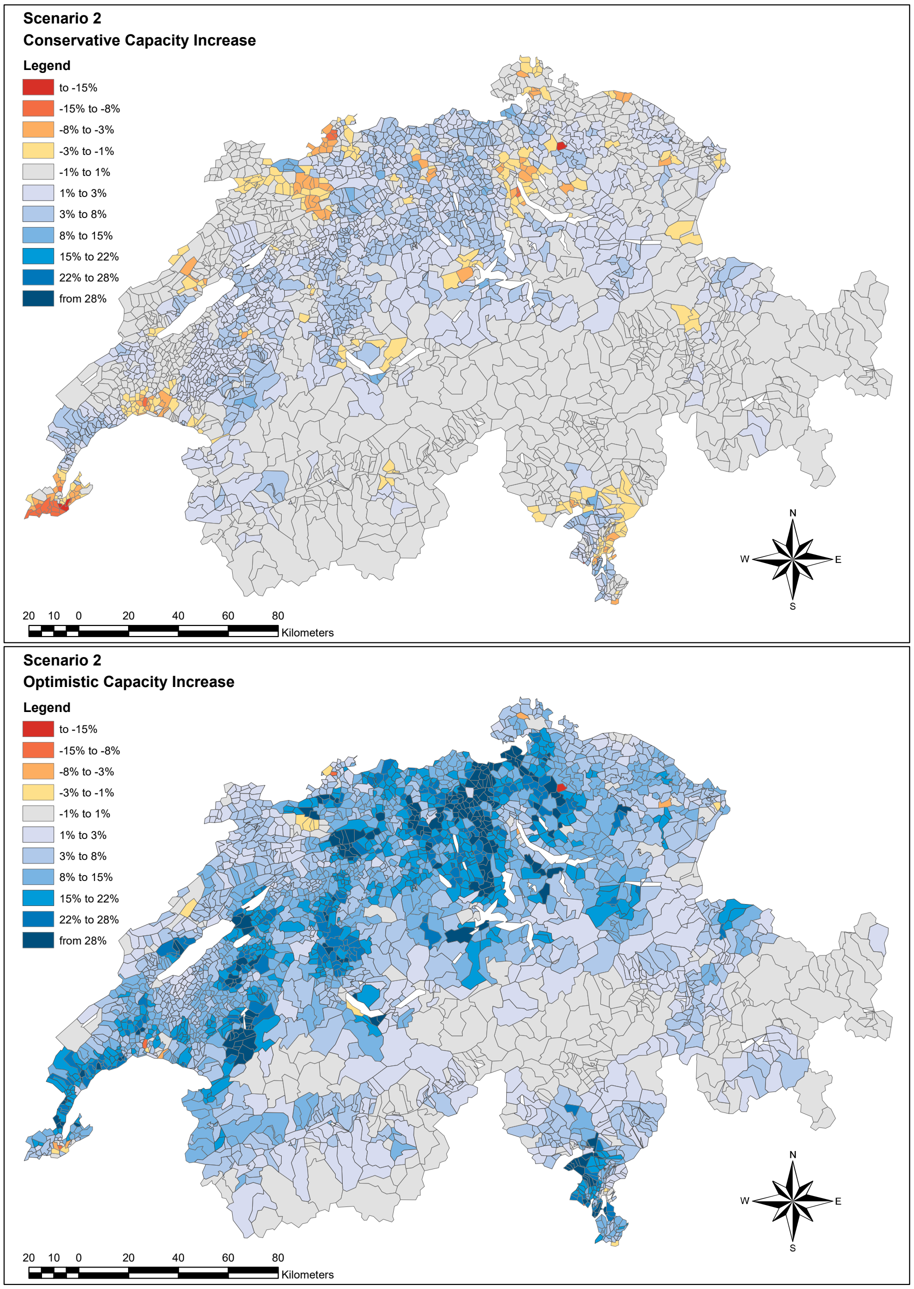

Figure 3: Relative changes in accessibility - scenario 2 [36]

and brought to their destination. Moreover, the service is assumed to offer private transfers, i.e. there is no ride-sharing[1]. Therefore, the accessibility impacts described in this scenario can be interpreted as a lower bound.

Since the highest level of automation is assumed, no driver's license is required to use the service. Moreover, owning a car is no longer necessary to benefit from the advantages of auto-mobility. Therefore in this scenario, the whole population - irrespective of age, driver's license or car ownership - is eligible to use this fleet of shared autonomous vehicles.

Given the high expected attractiveness of the service and the fact that such a large-scale scheme will be able to operate very efficiently and therefore to offer competitive prices [13, 12, 15, 5], it is assumed, that public transportation users gradually shift towards this new scheme whilst their origin-destination relations remain the same:

$$D^{'}_{i,j} = D_{i,j} + \gamma \cdot PTD_{i,j} \qquad \gamma \in \left\{\frac{1}{3}, \frac{2}{3}, 1\right\} \qquad \forall i, j$$

with $D_{i,j}$ being the original car travel demand and $PTD_{i,j}$ being the public transportation demand from origin i to destination j. In this scenario, the immobile population as well as walkers and bikers are not expected to change their behaviour.

Although such a large-scale scheme will operate very efficiently, there will still be relocation trips necessary. Fagnant and Kockelman [12] estimate that 10% of the rides in such a scheme are empty. Given that their work was on an urban scheme, whereas this research covers a nation-wide service, empty rides

[1]In some earlier research, it is assumed that vehicles may also be shared by strangers (pooled trips). However, given the already low expected operating cost of autonomous taxi fleets offering a private service, it is yet unclear to what extent customers will be willing to join pooled trips for marginal savings. [5]

are assumed to add 15% to the total travel. As before, it is assumed, that the origin-destination-relations of empty rides match those of the travel demand:

$$D^{''}_{i,j} = D^{'}_{i,j} \cdot 1.15 \qquad \forall i, j.$$

4.3.2. Results

Again, the most extreme case, in which the travel demand for autonomous vehicles consists of the original car demand plus the full original demand for public transportation plus an additional 15% empty rides, is presented. Given the spatial differences in public transport use, the increase in demand (without empty rides) varies between 0 (for some rural municipalities) and 180% (Zurich city center) Again, for some municipalities this represents a stronger increase in demand than in road capacity..

The results are presented in Figure 4. The figure shows that in the conservative scenario, accessibility gains in the countryside are accompanied by substantial decreases in the larger agglomerations of Berne and Zurich. In total, 85% of the municipalities would benefit from higher accessibility, whilst 15% of the municipalities (mostly cities) suffer from accessibility losses of up to 29%. Thus, when weighted by population size, this scenario results in an overall 1.4% increase in accessibility.

When looking at the optimistic capacity scenario, substantial increases in accessibility can be observed throughout the country except for the agglomerations of Berne and Zurich, for which lower accessibility is expected. Since in this case, the substantial gains in the countryside offset the losses in cities, an overall accessibility gain of 10.3% (weighted by population) is observed.

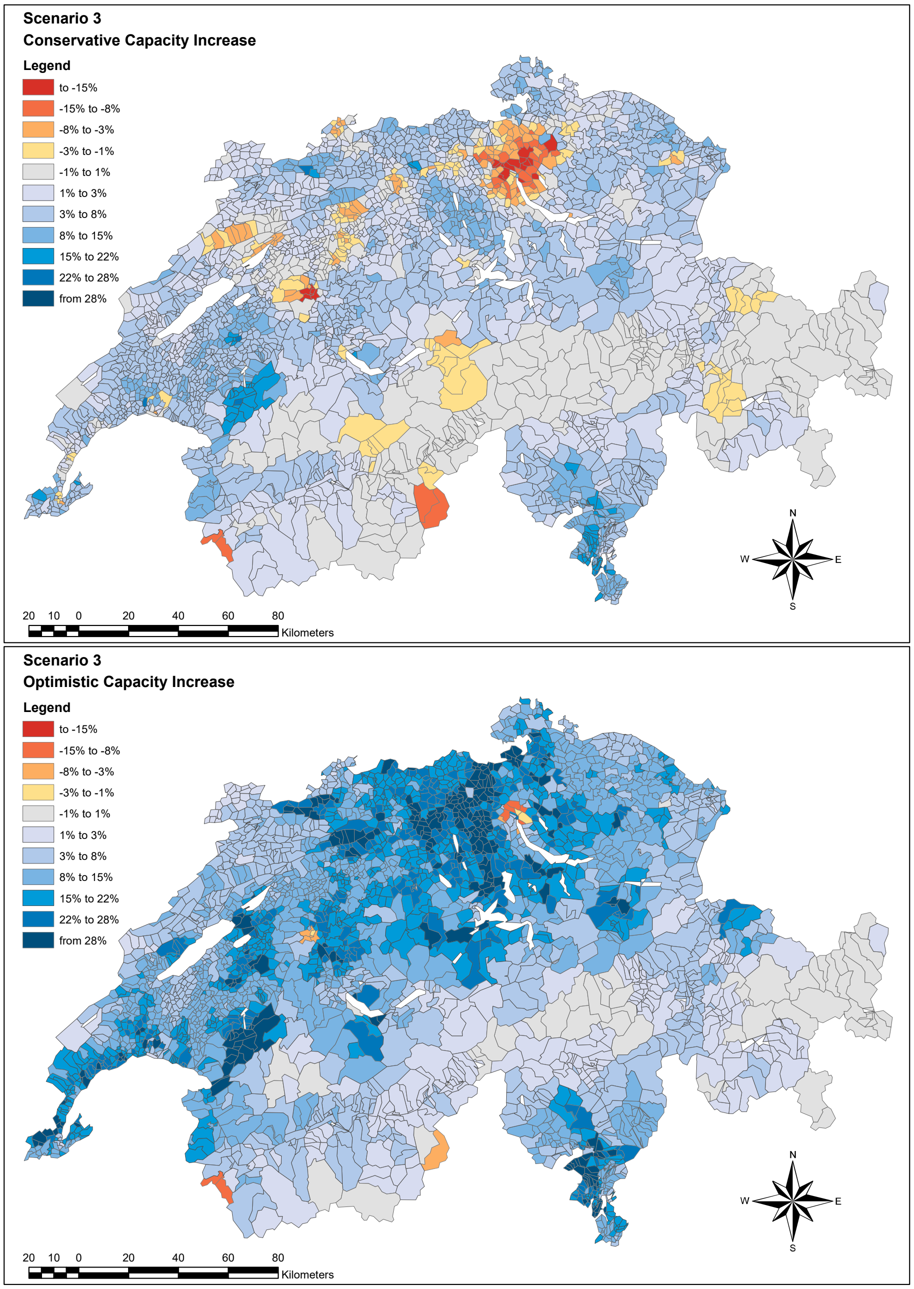

Figure 4: Relative changes in accessibility - scenario 3 [36]

5. Induced Demand

Higher accessibilities induce travel demand [22], which in turn lowers the expected gains in accessibility generated by autonomous vehicles. In order to quantify this effect, the Swiss guideline for an activity-based analysis of induced demand [43] is applied to scenario 3.

In contrast to the formulation by Hansen [25], the guideline uses a logarithmic formulation of accessibility:

$$A_i = \ln\left(\sum_{c_{ij}} X_j \cdot e^{-\beta \cdot c_{ij}}\right)$$

As stated above, in this research, the generalized cost c_{ij} is simplified to the travel time in the assigned network. The induced demand is then calculated in the following way [43]:

1. The accessibilities are calculated for both the baseline scenario and the new scenario using the above formula.
2. For each municipality, the relative change in accessibility is calculated as
$$\delta_{A,rel} = \frac{A_{\text{after}}}{A_{\text{before}}} - 1.$$
3. The relative change in accessibility is multiplied with the demand elasticity $\epsilon = 0.44$ to obtain the relative change in demand $\delta_{D,rel}$.
4. The origin-destination matrix is updated using
$$D_{ij}^{'} = D_{ij} * (1 + \delta_{D,i}) \quad \forall i, j.$$
5. The new demand is assigned to the network and the procedure repeated until only convergence is reached.

Figure 5 shows the relative changes in logarithmic accessibility for all municipalities given scenario 3. The figure shows that for most municipalities, the logarithmic accessibility has changed only marginally compared to the base

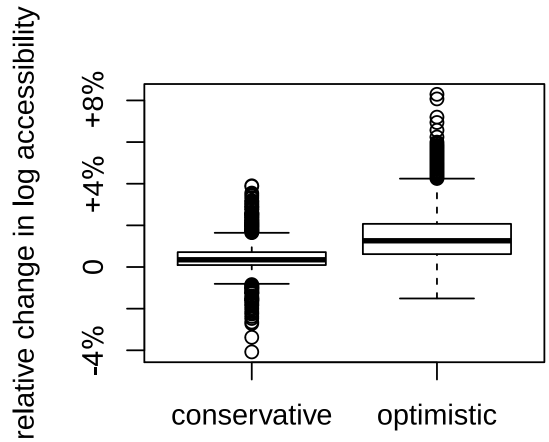

Figure 5: Relative changes in logarithmic accessibility for Swiss municipalities in scenario 3.

case. Therefore, it is well justifiable to use a linear approximation such as the one from the Swiss guideline [43]. In turn, only minor changes in travel demand are to be expected.

The results presented in Figure 7 confirm this expectation. The induced car travel is calculated to 120 000 km for the optimistic capacity scenario, which corresponds to only 0.1% of the total demand. Hence, the increases in demand are only minor and occur mainly in rural municipalities in the northern part of the country as well as in the Geneva area. Thus, when comparing the results to Figure 4, it can be observed that the induced demand evoked by the changes in accessibility does not significantly alter the overall accessibility impact of autonomous vehicles.

As a result, a mobility scheme as described in scenario 3 would cause substantial changes in accessibility. However, the actual form of those changes strongly depends on the assumed increase in road capacity.

In the case of the conservative estimate for capacity increase, agglomeration centers such as Zurich or Berne will suffer from substantial losses in accessibil-

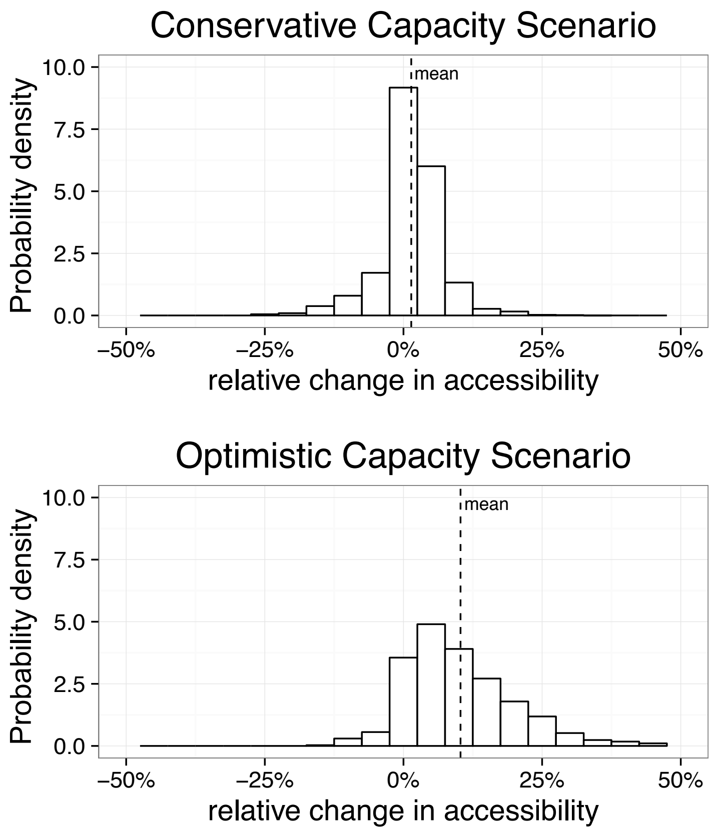

Figure 6: Relative changes in accessibility - scenario 3 with induced demand

ity whilst smaller, rural municipalities in the northern and western part of the country as well as in the canton of Ticino benefit from slightly higher accessibilities. Weighted by population size, the average accessibility is increased by 1.4%

Assuming the optimistic estimate for the capacity increase, the picture changes (compare Figure 6). Only the agglomerations of Zurich and Winterthur and the city of Berne suffer from decreased accessibility, whilst the (mostly rural) remainder of the country sees substantial increases in accessibility of up to 76%. Averaged by population size, the scenario results in a 10% increase in accessibility.

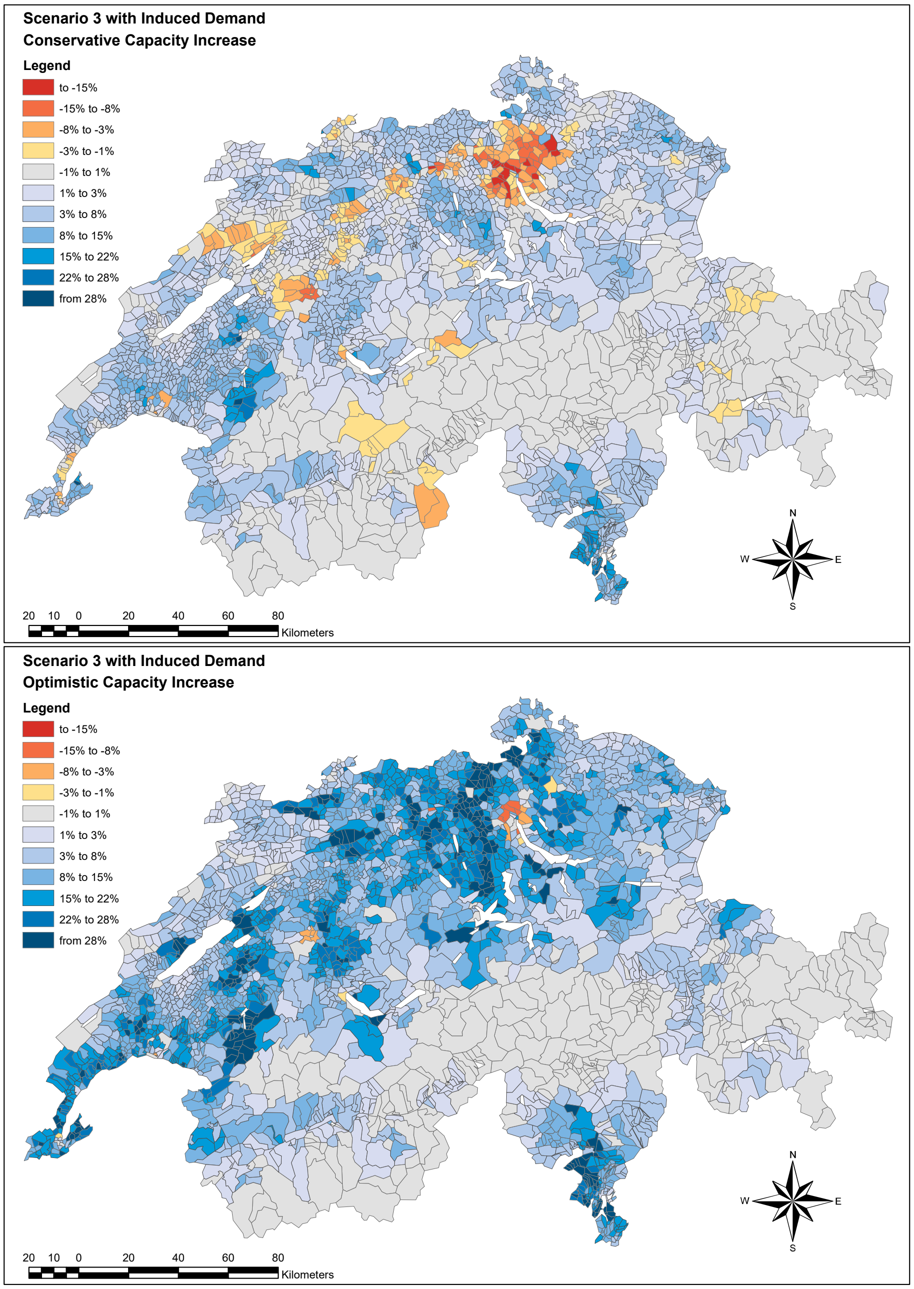

Figure 7: Relative changes in accessibility - scenario 3 with induced demand [36]

6. Discussion

The three scenarios analyzed in this research represent different realizations of autonomous vehicles: The first scenario represents a transition phase, in which vehicles can drive autonomously on motorways, but have to be driven manually otherwise. The second scenario represents a case which assumes private vehicle ownership as today - but with fully autonomous vehicles. It therefore assumes, that the rise of autonomous vehicle technology does not trigger new business models in mobility. This is in contrast to the third scenario, in which a fleet of shared autonomous vehicles supersedes public transportation and private car ownership. According to earlier research [13, 12, 15, 5] as well as industry developments [44], especially the third scenario is a likely future state.

As described above, autonomous vehicles substantially change the accessibility landscape for Switzerland. Although the increase in accessibility is strongest in the transition scenario, also the other two scenarios have a considerable impact.

In all scenarios, the accessibility impacts of autonomous vehicles can be differentiated between three types of regions: Remote alpine municipalities are mostly unaffected, because already in the base case, the loads on the street network in their surroundings are far below the capacity level. The strongest positive impact on accessibility is observed for well-connected exurban and rural municipalities. Here, today, access to/from the agglomerations is significantly degraded due to congestion on the arterial roads and highways during peak hours. An increase in capacity on those roads reduces travel times and therefore increases the accessibility of such places.

The third region are the larger cities, in which weaker or even negative impacts are observed. This is, because the relative increase in demand to and from the cities exceeds the relative increase in road capacity. Especially in scenario 3, the increase in demand is the strongest, where today there is substantial use of public transportation, - in the larger cities. Yet, such an effect would be expected not only for Zurich and Berne, but also for Basel and Geneva. However, in Basel, inbound commuters are less relevant than in other cities, whereas in Geneva, public transport plays a less important role. Moreover, both cities sit at the country's border, which means their neighboring municipalities are represented in less detail.

Another interesting observation is, that whilst for the conservative estimate for capacity increase, the three scenarios yielded completely different results, only minor differences were observed for the optimistic estimate for capacity increase. This means that the stronger the technically possible increase in capacity, the less the accessibility impacts depend on the actual implementation of autonomous vehicles.

To better understand the size of the accessibility impacts of autonomous vehicles, it helps to compare the results of this research with historical data. In a comprehensive approach, Axhausen et al. [45] have calculated the accessibilities of Swiss municipalities in logarithmic form. For the time between 1950 and 2000 they report road-based accessibility scores for each decade. According to their results, there has been a 10% increase in road-based (logarithmic) accessibility between 1950 and 2000, which is mostly due to substantial investments in the national road network during the post-war years. Since 1970, the road-based (logarithmic) accessibility has increased by 1% per decade. Therefore, according to Figure 5 the accessibility impacts of a shared autonomous vehicle fleet are equivalent to up to 15 years of infrastructure investments in the optimistic capacity scenario. Yet, the actual impact will be even higher given that a fleet of shared autonomous vehicles will also serve public transport users, for which (logarithmic) accessibility scores typically are 35% lower than for cars [45].

It is striking that such a gain in accessibility is achieved whilst absorbing the whole public transport demand and without even considering ride-sharing schemes or larger vehicles such as autonomous buses. In addition, it was assumed that the speed limits remain at today's level. Higher speed limits are possible with autonomous vehicles and may further enhance their impact on accessibilities.

Of key interest for future transport planning is the question, how public transportation and a fleet of shared autonomous vehicles would interact. As already shown earlier [5], public transportation is only economic for relations with high demand (i.e. more than 20 passengers per departure) whereas in situations with a lower demand, a fleet of shared autonomous vehicles can serve the demand at lower cost and possibly even faster and more comfortably. The results of this research indicate a similar balance: Whilst in rural areas and smaller cities, a fleet of shared autonomous vehicles can serve the full motorized travel demand and still increase accessibilities (reduce travel times), the picture is different in larger cities such as Zurich or Berne. Here, the additional demand outweighs the capacity benefits and would lead to substantial increases in travel times and therefore lower accessibilities. Thus, it can be expected, that public transportation will still be required in larger cities and can play an important role on regional relations with sufficient demand. Yet, particularly in rural areas and smaller cities, it will likely be superseded by shared autonomous vehicle fleets.

This research is meant to be a first exploration of the magnitude of the accessibility impacts of autonomous vehicles. It relies on various assumptions and simplifications given that today, many key aspects such the pricing schemes, service levels, comfort, reliability and consumer preferences of future autonomous vehicles as well as the characteristics of their traffic flow, of the expected empty rides and the impacts on local choices and trip lengths are largely unclear. In this light, the three scenarios above have been chosen as generic representatives of each of the possible generalizations. However, empirical data can be included in the model once it becomes available.

7. Conclusion

The results of this research confirm earlier findings [27, 28] indicating that substantial increases in accessibility can be expected from autonomous vehicles. Yet, the magnitude of the disruptions they will cause, strongly depends on the actual capacity gains autonomous vehicles can achieve. They may range up to an equivalent of 15 years of infrastructure investments. Considering, that this effect is reached whilst absorbing the full public transportation demand and despite neglecting various effects likely enhancing the impact of autonomous vehicles, this corresponds to a quantum leap in accessibilities [45].

Depending on the scenario, also the land-use impacts of autonomous vehicles will be substantial. In fact, the results show that well-connected rural municipalities have the strongest increase in accessibility, whilst the effect in city centers is much less strong or even negative. However, from history, it has become clear that such a pattern paves the way for more urban sprawl [24, 46]. It is therefore advisable for planning authorities to take up on this matter to be able to keep control over the upcoming disruption.

Moreover, this research sheds some more light on the competition between autonomous vehicles and public transport. It shows, that from a capacity standpoint, even in the most extreme case (low road capacity increases, huge increases in demand, peak hour traffic situation), fleets of autonomous vehicles will generally be able to serve the full transport demand including both car and public transport demand. Only in large agglomerations, where highest transport demands meet limited road capacities, public transport will still be required. Yet, with higher road capacity gains, the area, in which public transport will be needed, is further reduced to only the centers of those agglomerations. In this respect, the results of this research draw a similar picture of future use cases of public transport and shared autonomous vehicles than earlier research on the cost structures of such schemes [5].

Given that many aspects of future autonomous vehicles are still unclear, this research provides first estimates of the accessibility impact of future autonomous vehicles. Although already alarming enough, the estimates of those accessibility impacts should steadily be refined as more information on the actual implementations and travel behavior impacts become available.

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