Urban road network performance with shared automated vehicles

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ABSTRACT

Automated vehicles are widely expected to bring about various benefits for (urban) transportation, e.g. by increasing road capacities and reducing generalized cost of travel. However, the latter may induce additional demand for road transportation, possibly counteracting gains in accessibility. Hence, the net impact of vehicle automation on road network performance is still unclear. This research uses the macroscopic fundamental diagram (MFD) to address this question for different levels of road capacity increases and modal splits between private and shared (i.e. public) transportation. To this end, various scenarios are tested in a simulation model for the morning peak hour for Zurich, Switzerland, as a case study, for which current demand levels for car and public transport are used. Yet, the results can be generalized to different city types. The analysis indicates that in car-oriented cities, vehicle automation will likely bring substantial benefits in network performance in current car-oriented cities, while for public transport oriented cities, substantial gains in road capacity of 40 % or more will be required to make up for the potentially substantial mode shift from public transport towards (pooled) cars. Moreover, results show that up to 75 % mode share of ride-sharing trips will be required to achieve a system-optimal state, which - depending on the technologically possible capacity gains - may even be inferior to the current state.

Keywords: self-driving vehicles ; automated vehicles ; macroscopic fundamental diagram (MFD) ; urban network, capacity

INTRODUCTION

Vehicle automation is widely expected to bring about large benefits for urban transportation, e.g. by making roads safer (1), by reducing costs of travel (2) and by potentially allowing a more sustainable transport system (3). Through operation as shared and/or pooled services, existing infrastructure and resources could be used even more efficiently (4). However, such benefits may also induce changes in travel demand, potentially counteracting the expected positive impacts (5, 6). At the same time, it is unclear how automation technology will impact urban road capacities (7). Hence, the question arises, how the obvious benefits can be harnessed, while staying within the physical capacity limits of the urban transport network.

Since the mechanisms of traffic flow are generally understood (8, 9), such a question can be broken down into assessing the respective parameter changes due to automation. In particular for road and intersection capacity, various such assessments already exist (7, 10, 11). Yet, these factors alone do not allow to estimate the effects of automation on the possible productivity of existing urban infrastructures (i.e. the number of completed trips in a network (12)), since characteristics of demand may also change. The theory of the macroscopic fundamental diagram (MFD) provides a link between physical limits and productivity of urban networks (12) and thus allows to analyze the impact of vehicle automation on network performance. The MFD abstracts urban road networks into a bathtub-like (13) reservoir with inflow, internal flow and outflow, where the two latter flows depend on the vehicle accumulation inside the reservoir.

In general, vehicle automation can be expected to affect network performance in two ways: They may increase road capacity through smoother driving and shorter minimum headways. However, if operated as shared taxis, they will also be moving bottlenecks (when stopping to allow passengers to board or alight) and induce higher vehicle miles travelled (VMT) through longer trip distances (through detours) and empty travel. Hence, the net impact will depend on the relative strength of the two effects.

This paper presents a first discussion on how automation of vehicles and their operation as shared and/or pooled services can improve the productivity of urban transport networks based on the MFD. We consider only two road surface modes: private vehicles and shared/pooled vehicles. The latter category may also include buses if defined as such. For each mode, corresponding MFDs are defined for the downtown area of Zurich, Switzerland, which are then used to simulate a typical morning commute in a simplified model (14). Scenarios with varying market shares of the different services are considered.

The remainder of the paper is organized as follows. In Section 2, earlier research on vehicle automation is discussed. Section 3 introduces the MFD and the relevant parameter changes to adapt it to (shared-) autonomous operations. Thereafter, we introduce in Section 5 the model used in this paper before showing the scenario analysis in Section 7. The results are discussed in Section 8, while Section 9 shows the practical implications of this research.

IMPACTS OF VEHICLE AUTOMATION AND SHARING

Automated driving technology (full automation (level 5) as defined by SAE International (15)) will likely trigger substantial disruptions in both transport demand and supply. By driving production costs of taxi services down to a level comparable with public bus services (2), such automated taxis will likely become a relevant mode of transportation, potentially substituting formal line-based public transport services, at least in lower-density environments. Also private vehicles will become more attractive when automated (16) as they may provide features of a personal chauffeur and errand boy.

Assuming a static demand, earlier research has shown that switching all car travel to automated taxis would allow to slash required fleet sizes by up to 90 % (17). In addition, it was found that 15 % of New York's current taxi fleet would be sufficient to serve all taxi trips, if rides were shared by multiple passengers (pooled taxis) (18). But through empty travel in an automated taxi scheme, total VMT would increase by 10 % (19), whereas for pooled trips, detours are required to cover the origins and destinations of all passengers (3.5 min in the study by Alonso-Mora et al. (18)). Yet, the assumption of a static demand is highly unrealistic. Not only will cheap automated taxis change the accessibility landscape and thus land-use patterns, they will also attract new user groups for road transport (5), thus substantially changing origin-destination relations and increasing demand. In addition, increasing urbanization in the future will add more pressure to urban transportation systems (20).

Vehicle automation will also have profound impacts on traffic flow characteristics: Faster reaction times of sensors will allow shorter headways and thus an increased road capacity. Benefits can be increased further by vehicle-to-vehicle communications allowing smoother driving and even shorter headways (10, 11). As a result, also stability of traffic flow will be higher (21). However, such analyses have mostly been done for highway traffic so far (22) and only rarely took into account legal standards of care, which may however limit the possible capacity gains (23). For urban road networks, capacity is mostly determined by intersection capacities (24). However, there is no agreement on the impacts of vehicle automation yet. While Fajardo et al. (25) and Li et al. (26) predict increases in throughput of up to 20 %, Le Vine et al. (7) even find a decrease in capacity, when restricting lateral accelerations to a level considered comfortable for passengers. In a highly integrated regime, removal of traffic lights may allow even more efficient operations (27), at the expense of cyclists and pedestrians.

A further way to increase road capacity may be achieved by vehicle right-sizing, i.e. by designing smaller, purpose-built vehicles. Also, policies such as speed limits may be adjusted in the light of increased traffic safety.

Since automated vehicles will likely be used like taxis, they will drop off passengers as close to their destination as possible (and the same for pick-up), thus blocking a lane during this dwell time unless dedicated infrastructure is provided. This is similar to buses, where the impact on performance has already been intensely studied, e.g. (28, 29, 30). For Uber services, earlier research suggests that this effect (along with empty VMT) causes substantial losses in network speeds (31). However, the resulting impact might be different if automated vehicles were in play.

This research aims to combine insights on trip characteristics and traffic flow parameters in a future regime of automated vehicles to study their impact on transport network performance using the macroscopic fundamental diagram (MFD). The focus of this study lies on full vehicle automation (level 5 (15)), acknowledging that a potential implementation of fully connected vehicles may allow further capacity benefits (10) in the distant future.

THE MFD AND VEHICLE AUTOMATION

The underlying idea of the MFD is to think of urban networks as a *bathtub* or reservoir (12, 13). All microscopic or local between-vehicle interactions affecting network performance are not explicitly considered anymore, but implicitly accounted for in the relationship between reservoir accumulation and reservoir outflow, the MFD (32). The MFD shape is - in theory - only dependent on road network structure, signal settings, route choice and the fundamental diagram (33, 34, 35). We ex-

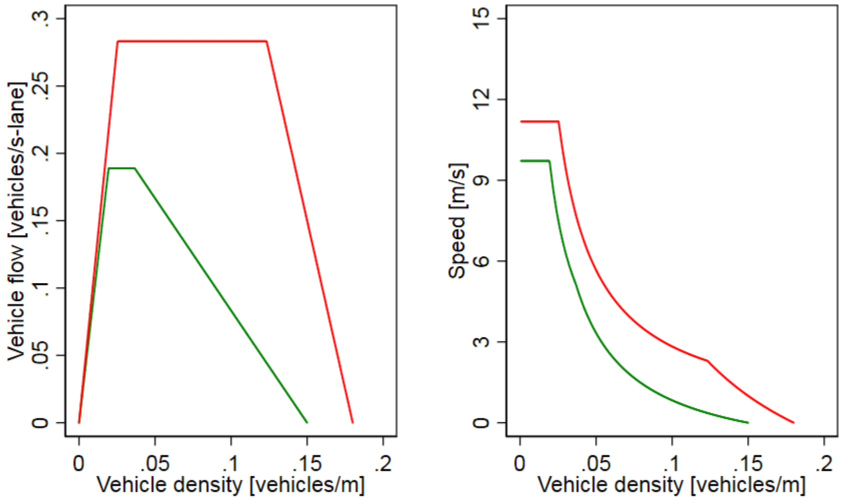


FIGURE 1 : A typical MFD for urban traffic with conventional car vehicles (green) and automated vehicles (red).

pect and consider that the effects of vehicle automation to affect in the first place the fundamental diagram with basic parameters: free flow speed, saturation flow, jam density and backward wave speed.

For the conventional case, the parameters for the city of Zurich are available from earlier research (36). Yet, in an automated regime, most of the parameters are likely to change due to the new technology. In essence, it is assumed that the free-flow speed u_f is only slightly increased because of the general political trend to limit or lower speeds within cities. Saturation flow is increased by 40 % and 78 % as suggested by Friedrich (11). With only minor changes in vehicles sizes, the jam density K_{jam} is expected to increase only marginally. Due to better reaction times, the wave speed w will also improve by almost 65 % as the assumed reaction time decreases from 1.4 s to 0.5 s (37). In contrast, Green time ratio is assumed unchanged to still be able to accommodate pedestrians and cyclists. Further, we assume that network structure (extent of the network and routing) remain unchanged.

Here, we simplify MFDs by a trapezoidal shape (38) given by Eqn. 1. The realized capacity Q typically follows from the product of saturation flow and average green time ratio (33) and the free-flow speed and backward wave speed accommodate already delays at intersections. In Table 2, the range of trapezoidal shape parameters are compared for conventional and automated private cars. To obtain a smooth and concave shape of Eqn. 1, we use the smooth approximation thereof as proposed by (39). Figure 1 compares the effects of automation on the resulting trapezoidal shape of the MFD for conventional cars (green line) and automated cars (red line) using the average of parameters from Table 2.

$$q(k) = \min\left(u_f k; Q; \left(K_{jam} - k\right) w\right) \tag{1}$$

Shared vehicles - either buses or shared/pooled AVs - usually have to stop at a distance d for boarding and alighting passengers where the vehicle stops for time τ. Hence, the average

	Unit	Conventional car	Full automation	Sources
Free-flow speed u_f	[km/h]	25 - 35	30 - 40	own assumption
Jam density K_{jam}	[veh/lane-km]	130 - 160	140 - 170	own assumption
Wave speed w	[km/h]	4.0 - 7.0	14 - 18	estimate based on van Arem et al. (37)
Capacity Q	[veh/h-lane]	400 - 700	560 - 980	Friedrich (11)
Saturation flow s	[veh/h-lane]	1 600 - 1 800	2 850 - 3 200	Friedrich (11)
Green time ratio G/C	[-]	0.4 - 0.5	0.4 - 0.5	own assumption

TABLE 1 : Comparison of trapezoidal MFD parameters

commercial free flow speed speed of shared vehicles can be described by Eqn. 2

$$v_{shared} = \frac{d}{d/u_f + \tau} \tag{2}$$

In application contexts, the MFD faces several important caveats such as heterogeneity in the distribution of traffic (40, 41) or loading and unloading effects in the network (42, 43), both of which lead to an inaccurate and biased MFD estimates. In this analysis, however, we do not address these effects as we want to understand traffic performance in an optimal case.

CASE STUDY

The analysis is conducted for the city center of Zurich, Switzerland, as shown in Figure 2. The city of Zurich has 425 000 inhabitants (1.3 mio in the metropolitan area). With 360 000 jobs located in the city, there is a substantial inflow of commuters each morning. Zurich residents frequently travel on active modes (i.e. walk or bike), 32 % of the trips are done using public transportation, 25 % using private cars. Overall, 24 % of the settlement area are devoted to transportation infrastructure. For the study area, the infrastructure for all motorized modes of transport currently is $L = 396km$ (lane kilometer), of which 75 % are assumed available for car traffic.

Data on the transportation network, as well as current travel demand data was available from the official macroscopic assignment model of the Canton of Zurich (44).

As discussed above, vehicle automation and the corresponding new service types will also affect demand characteristics (Eqn. 2). Dwell time τ was measured at the passenger drop-off area at Zurich airport. For Uber vehicles dropping off passengers without heavy luggage, average time between arrival of the vehicle and continuation of the drive was 30 seconds. Hence, total dwell time per passenger is $\tau = 1\,min$ ($30\,s$ boarding plus $30\,s$ alighting). The average trip distance l_p was obtained from the Swiss national household travel survey (45), which indicates an average of $3.4\,km$ for car trips within the city of Zurich (2). For pooled trips additional dwell time of $1\,min$ is assumed (two pick-up or drop-off activities). Given an acceptable additional travel time of $3.5\,min$ (18), the remaining $2.5\,min$ of travel time translate into a 25 % higher trip distance for pooled trips (at $20\,km/h$ average network speed). For pooled trips, vehicle occupancy ρ was assumed 2.6 passengers (in accordance with Bösch et al. (2)).

In this analysis, the morning peak hour is simulated for the city of Zurich, Switzerland. The simulation calculates the traffic states minute-by-minute from 6 am to 10 am. Travel demand is assumed exogenous (and static). Departure rates are given by a gamma distribution, which was fitted against trip data from the Swiss national household travel survey 2015 for Zurich (45)) and

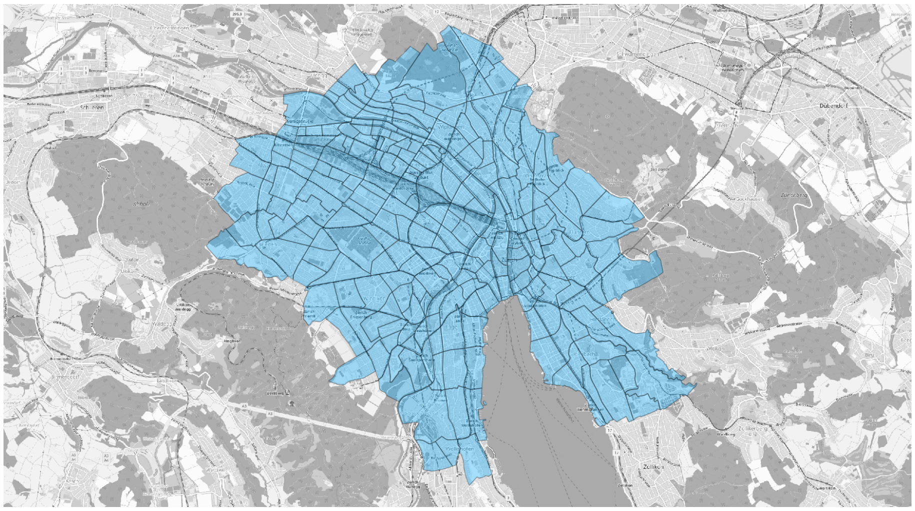


FIGURE 2 : Study area (blue).

reflects the totals for car and public transport given by the Cantonal traffic assignment model (44). The fitted distribution is presented in Figure 3. The total inflow is $q_{in} = 69602$ vehicles (7am to 8am). To this number 30 % have to be added to account for outbound traffic. We add another 30 % to capture the entire morning commute, i.e. from 6 am to 9 am (multiplier estimated based on (45)).

In the simulation, mode choice is not modeled explicitly as we want to understand how the performance of the system varies when the demand is distributed by experimental design over private AVs and pooled AV taxis. Thus, a fixed modal split between private (ψ) and shared ($1-\psi$) AVs is defined for each scenario.

THE MODEL

For simplicity, we assume that each mode runs on dedicated infrastructure, i.e. designated lanes, and that both modes do not create any negative externalities to vehicles of the other modes. This kind of lane separation already exists in many cases such as dedicated bus lanes or HOV lanes on motorways. The share of the network for private vehicles is η and for shared vehicles $1-\eta$. As emphasized before, we want to understand the optimal traffic outcome that can be possible or an upper bound to the performance. However, in reality, substantial interactions would have to be expected (at least at intersections), and thus decrease performance. Consequently, the above assumptions mean that each mode has its own reservoir and MFD.

We simulate the morning peak with an interval of one minute. In each interval, we derive from the demand shown in Figure 3 the reservoir inflow q_{in} for each mode. The constant speed at which these vehicles travel through the reservoir is determined by the current space mean speed in the reservoir as derived from the MFD based on the current accumulation of vehicles in the reservoir. The vehicles stay in the reservoir at this speed until they finished their trip after an exogenous trip length l_p or l_s. In case of shared AVs, passengers are pooled into vehicles with on average ρ persons per vehicle. Although this might be rather simplistic, we consider the information loss of the model to be marginal as demand is changing only slowly. Further, if using in each simulation step the precise speed information, the simulation has to account for the fact that the information of speed change can not travel faster than the vehicles and is not instantaneous which is a non-trivial

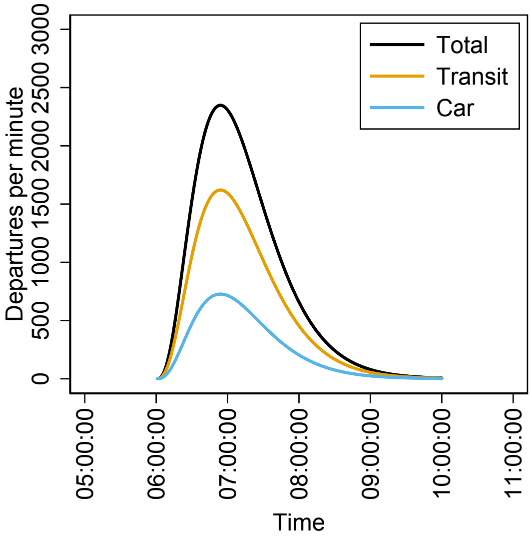


FIGURE 3 : Total departures and per means of transportation.

task (14).

In Figure 4 we show the model results for the current situation for conventional cars. The model results match closely the observed patterns from empirical observations in Zurich (36). We do not show the model results for the public transport system because the decrease in commercial speeds and thus congestion is negligible.

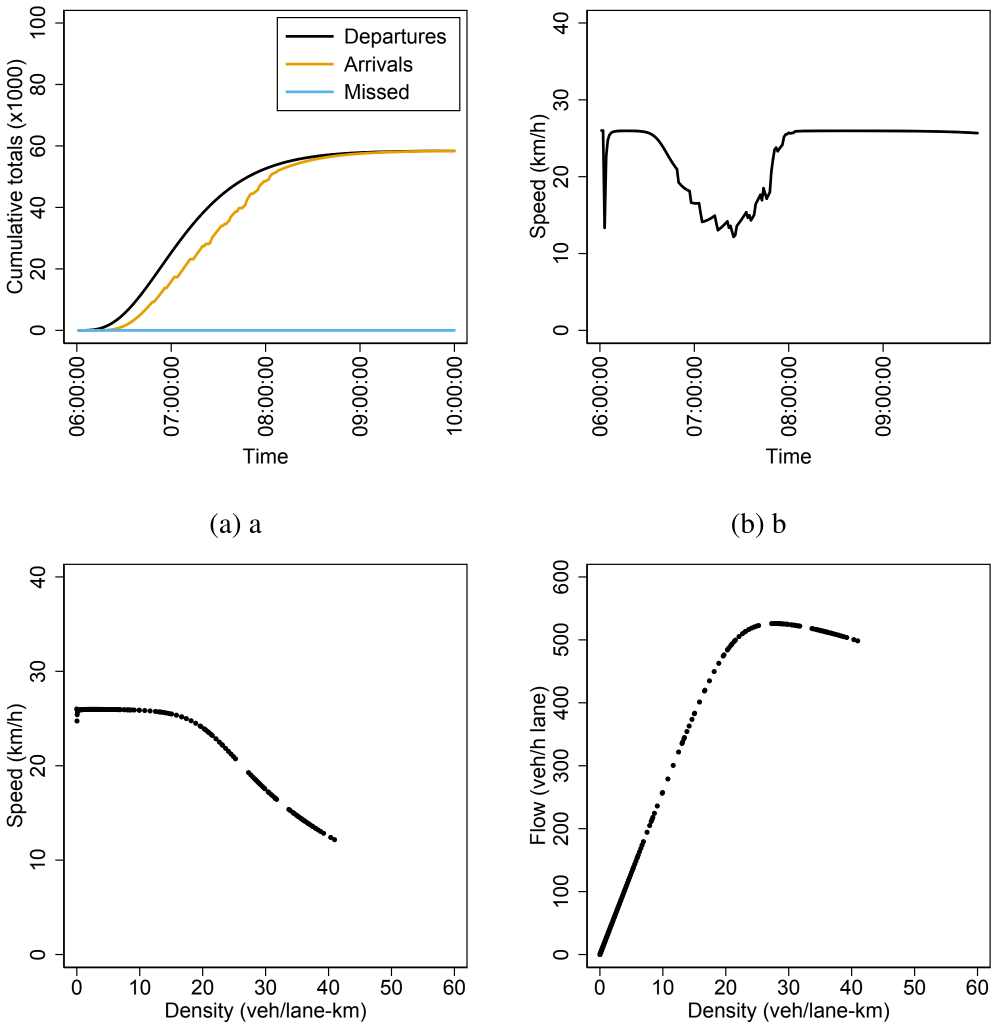
SCENARIO ANALYSIS

To analyze the performance of urban road networks in an automated vehicle age, we first consider that all trips currently made by private cars will be covered either by private automated vehicles or pooled automated taxis (i.e. taxis with ride-sharing). However, given the substantially lower expected prices of (pooled) taxi services, they will likely attract public transport users. To account for this competition, in a second case it is assumed that all street-bound public transport trips (i.e. buses and trams) will also be done by private automated vehicles or pooled automated taxis. Additional demand by new user groups or induced demand by lower generalized cost of travel are neglected in both cases (compare Meyer et al. (5)). In this sense, together with omitting between-mode interactions on the roads, the results of this analysis can be regarded as best-case scenarios or upper bound estimate to traffic performance. Therefore, the actual future network performance may likely be worse.

To capture the current uncertainty in both impact on road capacity as well as the operational implementation of automated vehicles, a number of different scenarios was analyzed. Scenarios were defined as combinations of three key parameters (c.f. Table 2):

- Impact of vehicle automation on road capacity. Although first estimates are available (11), there still is substantial uncertainty (7, 23). Hence, three levels (no change, 40 % increase (11) and 80 % increase) covering the most likely outcomes are considered.

- Share of trips conducted with private automated vehicles (vs. shared automated taxis) - from 0 to 100 %.



(a) a

(b) b

(c) c

(d) d

FIGURE 4 : The morning commute for conventional private vehicles for the calibrated model.

	Parameter	Levels		
γ	Capacity impact of automation	0 %	+40 %	+80 %
ψ	Share of demand for private transport	0 %, 5 %, 10 %, ... 100 %		
η	Share of network for private transport	1/3	1/2	2/3

TABLE 2 : Parameters and their levels

- Share of infrastructure devoted to private cars (vs. pooled automated taxis). For computational reasons, the two modes are assumed to travel on separate infrastructures. A practical interpretation would be the passing lanes for pooled taxis similar to today's HOV lanes on highways in the United States.

All scenarios were then simulated in the model and analyzed with respect to the resulting network productivity as measured in lowest space mean speed observed during the morning peak.

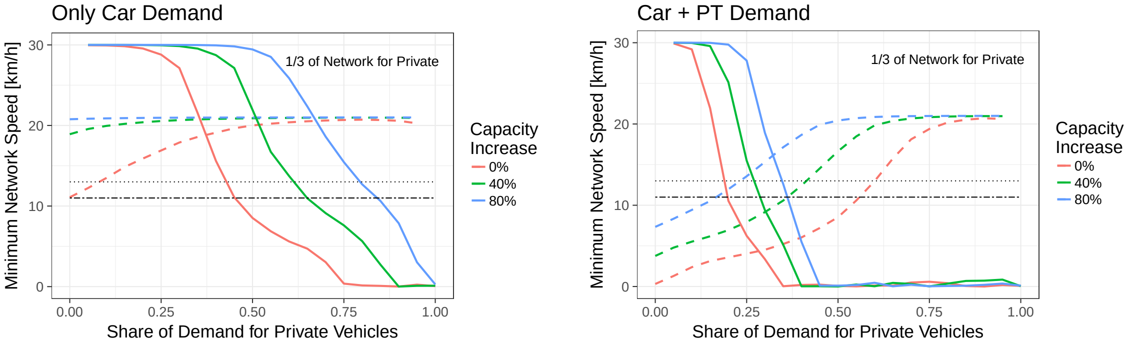
RESULTS

All combinations of the three key parameters were simulated in the model. The most relevant outcome are the network speeds. Figure 5 presents the minimum average network speeds for the two modes between 7 am and 8 am and compares them to today's network speeds of cars and tramways in the city center.

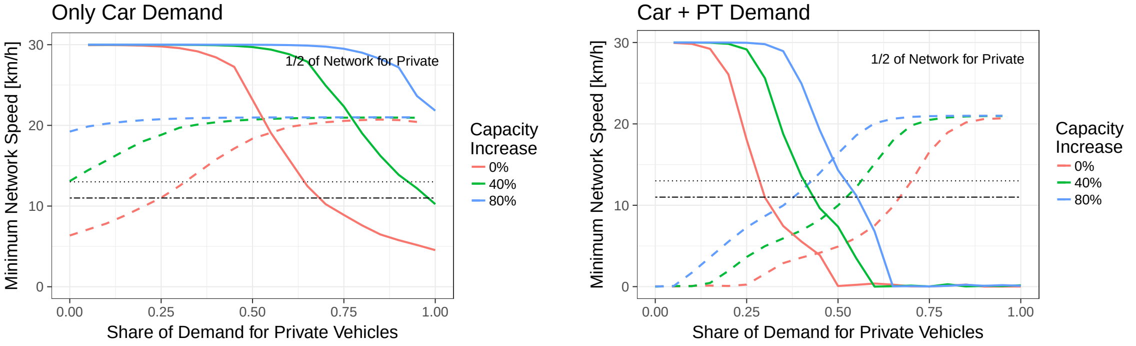
The results indicate that, naturally, maximum speeds are higher for private cars than for pooled taxis (because of the additional dwell times). Moreover, when a higher share of demand is assigned to private vehicles, speeds for private cars drop and vice versa. Moreover, changes in the split of the network available for the two modes shift the curves to the left or the right. In general, the highest minimum speeds for both modes are achieved when the capacity split equals the split of demand for the two modes.

A key insight from Figure 5 can be taken from a comparison with current car and tram speeds. For a static car demand (only today's car trips), almost all scenarios suggest substantial improvements (up to 70 % increase in speeds) in network performance, partly because of a more efficient use of vehicles (through pooling) and partly through potential capacity benefits of vehicle automation. However, the outcome is less clear when considering the full demand (car plus street-bound public transport). Hence, the latter case has to be studied in more detail. In fact, Figure 5 indicates that only at an 80 % capacity increase, the road network would be able to cover the whole current travel demand (assuming zero induced demand) and still improve the level of service. In the more likely case of a 40 % capacity increase, network speeds for both modes would be 25 % lower than for current public transportation. Without any capacity increase, minimum network speeds would plummet to below 5 km/h (65 % decrease) with probably substantial implications on land prices and social welfare. Hence, future network performance will strongly depend on the capacity gains achievable by vehicle automation.

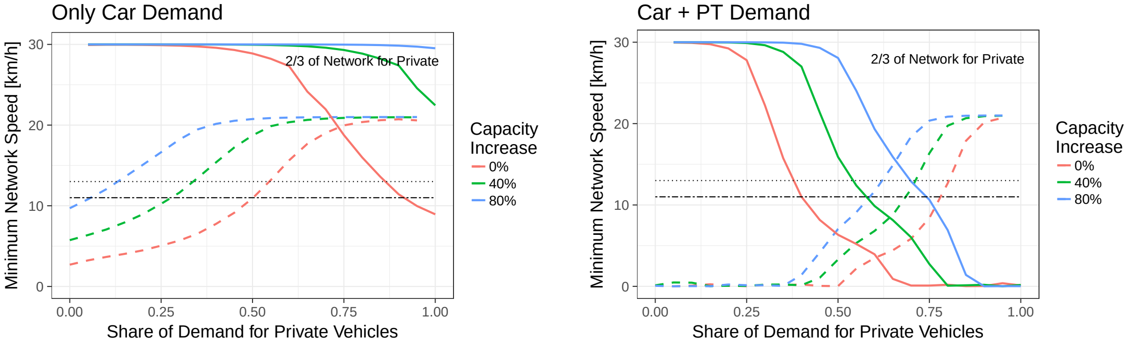
Yet, for network performance, not only the minimum speeds are important, but also the evolution of average network speeds throughout the study period. Figure 6 presents the speeds for selected scenarios (all for the case of full motorized travel demand). The plots can be compared to the current situation shown in Figure 4. In the current case, speeds decrease from 27 km/h at 6.30 am to 13 km/h around 7.30 am, but recover soon to reach the 27 km/h level soon after 8.00 am.



(a) 1/3 of network available for private vehicles. (b) 1/3 of network available for private vehicles.

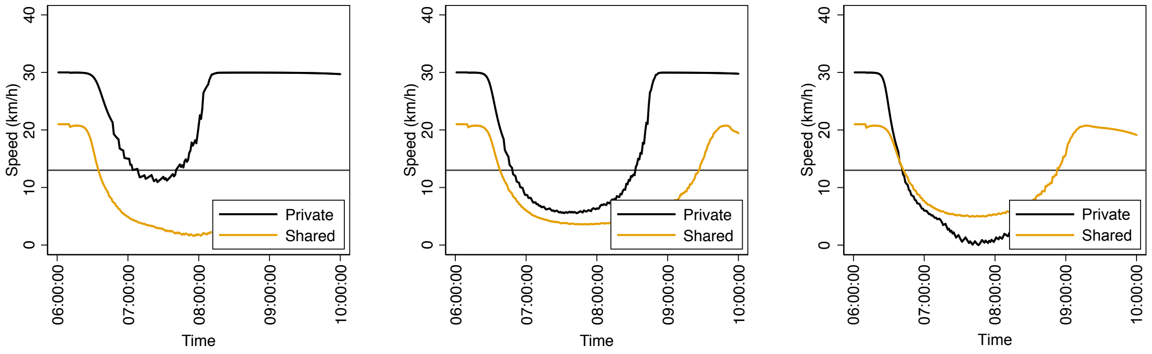


(c) 1/2 of network available for private vehicles. (d) 1/2 of network available for private vehicles.

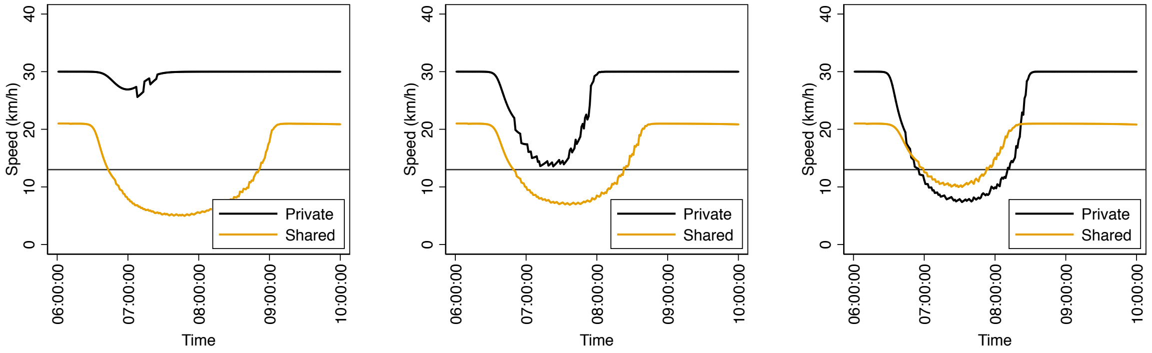


(e) 2/3 of network available for private vehicles. (f) 2/3 of network available for private vehicles.

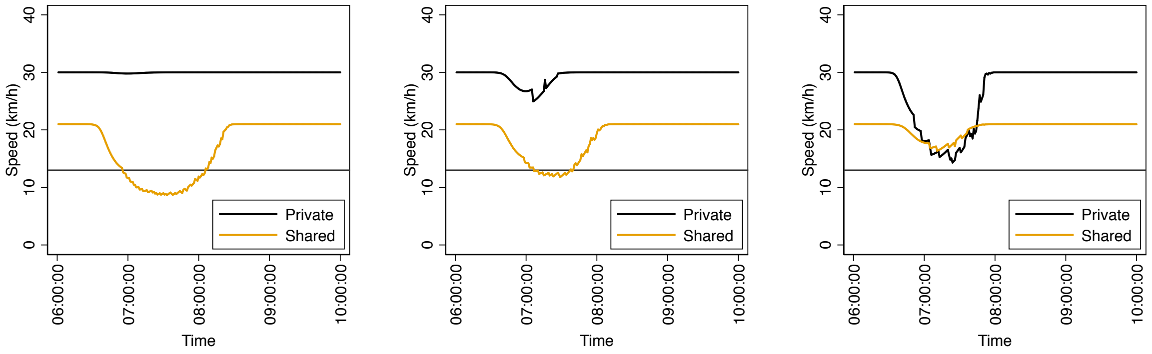
FIGURE 5 : Minimum network speeds for shared taxis (dashed) and private vehicles (solid). The dotted line provides the current network speeds of trams (13 km/h) as a reference; dash-dotted is the current speed of private cars during peak hour (11 km/h).



(a) $\gamma = 0\,\%$, $\eta = 1/2$, $\psi = 30\,\%$ (b) $\gamma = 0\,\%$, $\eta = 1/2$, $\psi = 40\,\%$ (c) $\gamma = 0\,\%$, $\eta = 1/2$, $\psi = 50\,\%$



(d) $\gamma = +40\,\%$, $\eta = 1/2$, $\psi = 30\,\%$ (e) $\gamma = +40\,\%$, $\eta = 1/2$, $\psi = 40\,\%$ (f) $\gamma = +40\,\%$, $\eta = 1/2$, $\psi = 50\,\%$



(g) $\gamma = +80\,\%$, $\eta = 1/2$, $\psi = 30\,\%$ (h) $\gamma = +80\,\%$, $\eta = 1/2$, $\psi = 40\,\%$ (i) $\gamma = +80\,\%$, $\eta = 1/2$, $\psi = 50\,\%$

FIGURE 6 : Network speeds for shared taxis (brown) and private vehicles (black). The tremor in the curves can be explained by the discrete simulation steps and the fact that vehicles may leave the network in platoons.

As shown in the first row in Figure 6, shifting all motorized travel demand of today towards private automated vehicles and pooled automated taxis without any capacity gains results in a substantial loss in network performance. In particular, speeds plummet below current minimum speeds and take much longer to recover. Since road infrastructure dedicated to public transport today is also considered available for the two modes in the simulation (in the form of lane-km), this means that buses and trams cannot be replaced by pooled taxis without increases in road capacity through automation.

In the second row, speed distributions are shown for a 40 % capacity gain through automation. While the results approach the current situation (especially Figure 6f), minimum speeds are still more than 10 % lower than today and also recovery after the peak hour takes slightly more time. Yet, given that the automated modes can be assumed more comfortable than driving a car or sitting in a bus, this situation may already constitute a general improvement compared to today. Yet, only with an increase of 80 % (third row), measurable efficiency gains (10 % or more) can be expected.

In addition, the simulation results can provide first insights on a favourable modal split between private automated cars and pooled automated taxis. To this end, the total travel times were calculated for each scenario. For the purpose of this first analysis, it is assumed that the system-optimal case corresponds to the case with minimum total travel time. In reality, disparities in values of time may translate into cases with higher shares of private modes being system-optimal. The results of this first analysis are presented in Figure 7.

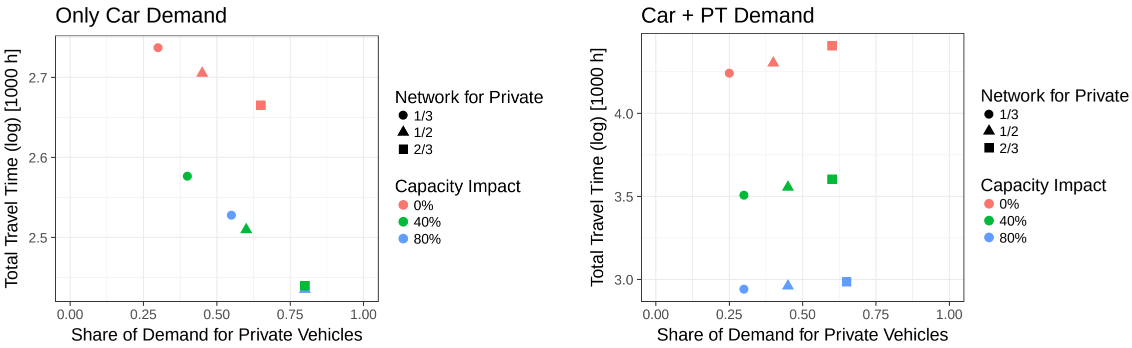
As a first insight, the optimal mode share of private cars depends on the capacity impact of automation: because pooled automated taxis need to stop more often for pick-up and drop-offs, they benefit less from capacity gains (and hence, speed increases) than private cars. In addition, it depends on the share of infrastructure available for this mode. However, in reality the same road infrastructure will likely be shared between private automated vehicles and pooled automated taxis.

Hence, most informative is the global minimum of total travel times. When considering only today's car demand and no capacity gain through automation, a 50 % mode share of private car trips (vs. 50 % shared rides) would be optimal. Assuming an 80 % capacity gain, this share would increase to 100 %. Interestingly, the results are substantially different for the case of the full motorized travel demand (car plus public transport): Here, minimal total travel times are reached at a private car mode share of 25 % - 30 % - for all three capacity scenarios.

DISCUSSION

Today's urban road networks are jointly used by fast-driving cars and slower buses and trams, which need to stop frequently to allow passengers to board and alight. Due to this behavior, such public transport vehicles represent moving bottlenecks (28, 30). In an era of automated vehicles, public transport services and private cars will likely be complemented and at least partially be replaced by (pooled) automated taxis. Yet, both automated taxis and automated private vehicles can be expected to frequently drop off and pick up passengers at the curbside, thus becoming moving bottlenecks in the network, too. Hence, the nature of mixed traffic with faster non-stopping vehicles and vehicles frequently stopping at the curbside will not change.

This research studies how the rise of private automated vehicles and shared automated taxis will impact performance of urban road networks. To do so, it uses a trip-based simulation tool based on the macroscopic fundamental diagram to study possible future scenarios. Although



(a) Only car demand (b) Car + PT demand

FIGURE 7 : Minimum of total travel times (log) for the different scenarios.

the assumptions for both the model and the future scenarios are based on earlier research, the approach relies on various simplifications, which should be addressed once better information becomes available. This concerns not only capacity impacts of vehicle-automation, but in particular travel demand patterns, which may be substantially different in the future (5). Methodologically, the solution of the bathtub model used in this research is not precise (46), but only approximated. However, this is not assumed to substantially bias the results.

Despite above limitations, this first analysis already provides relevant insights: First, it is shown that assuming only current demand for car-travel, vehicle automation may indeed allow substantial increases in network performance (as suggested earlier (10, 11)). The positive impacts scale with the possible capacity gains through automation and may be further increased by an uptake of shared automated taxis.

However, vehicle automation may not only increase road capacity, but also reduces taxi fares to a level comparable with public transportation. Moreover, it may allow a more efficient use of in-vehicle time. Both effects make car travel (individual or pooled) more attractive and are hence likely to attract current public transport users (2). For the analysis, the extreme case of all current bus and tram users switching towards car travel was analyzed. In fact, this may even constitute a conservative estimate of future demand given that may be substantial demand increases through new user groups (e.g. children and elderly) or induced demand effects due to higher comfort levels or changed land-use patterns. The results show that in such a case, substantial capacity gains of at least 40 % (the level expected by Friedrich (11)) will be required to maintain the current network performance.

On a second note, the results show that a large share of pooled taxi trips is required to achieve a system-optimal state. Yet, it is expected that pooled rides will not be substantially cheaper than individual rides (2). Moreover, higher privacy and comfort will likely outweigh the small differences in fares.

CONCLUSION

The results of this research show that vehicle automation will impact cities differently. The first case of "only current car demand" can be thought to apply to car-oriented North American cities, e.g. Los Angeles, CA. In such cases, vehicle-automation will likely bring substantial benefits in network performance. Moreover, cheaper taxi travel may in the long-run even reduce space requirements for parking.

The second case (current car + bus/tram demand) applies to transit-oriented cities like Zurich, Switzerland. In those cities, replacing the existing public transport will likely decrease productivity of networks, and thus accessibility, with substantial economical ramifications (47). Yet, given the low expected cost of automated taxi services and the small fare difference between individual and pooled taxis (2), strong policy measures will have to be developed to maintain a high level of public transport use. Without such measures, only capacity gains of 40 % or more will allow to maintain the current level of network performance. However, although such high capacity increases were predicted by early research (11), later studies expect the true impacts to be much smaller (7). In reality, required capacity gains may even be higher due to induced demand and new user groups.

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AUTHOR CONTRIBUTIONS

H. Becker and A. Loder conceived the study and performed analysis. All authors prepared and approved the manuscript.

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