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# A Systemic Analysis of Impacts of Individual and Shared Automated Mobility in Austria

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**Abstract**

**Rationale**: Increasing digitalization and automation is expected to significantly change the transport system, mobility and settlement structures. A decade ago automated, self-driving vehicles were nothing more than an unrealistic (boyhood) dream. But today the concept of highly and fully automated vehicles is rapidly becoming a reality, with a series of real-world trial applications underway. Government plans and industry predictions expect automation to be introduced from the early 2020s onwards. Nevertheless, there is still a high level of uncertainty in which form and to what extent automated vehicles will enter the market. Furthermore, there are ongoing discussions concerning net effects of positive and negative aspects of automation.
**Background**: The authors have been involved in several research projects analyzing potential impacts of automated driving. The EU funded project CityMobil (Towards Advanced Road Transport for the Urban Environment) was one of first to address automated driving on a large scale. As part of this project the System Dynamics based model MARS (Metropolitan Activity Relocation Simulator) was adapted to assess scenarios of automated driving in four European cities. Simulations demonstrated that automated vehicles integrated into public transport have a potential to reduce car kilometers travelled and improve carbon footprint. On the contrary, privately owned automated vehicles lead to an increase in car kilometers travelled and carbon footprint, unless propulsion technology is changed.
While the focus of CityMobil was on the urban scale, the nationally funded Austrian project Shared Autonomy (Potential Effects of the Take-up of Automated Vehicles in Rural Areas – own translation) focused on rural areas. The findings of Shared Autonomy show potential contributions of automated cars to improve the environmental situation and social inclusion in rural areas.
Finally, the nationally funded Austrian project SAFiP (System Scenarios Automated Driving in Personal Mobility) takes a look at the national territory of Austria.
**Method**: The relationship between vehicle automation, travel demand and environmental effects consists of a multitude of complex cause-effect-chains. The toolbox of System Dynamics offers appropriate methods to tackle such complexities. Causal Loop



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Diagrams are used to analyze and discuss relevant cause-effect-chains and are used to adapt an existing Stock-Flow-Model of the Austrian land use and transport demand system. The modified Stock-Flow-Model is used for a quantitative impact assessment. Sensitivity analysis in form of Monte-Carlo-Simulations is employed to tackle the high level of uncertainty concerning key factors.
**Findings, results**: The key factors, influencing mode choice and travel demand, are generalized costs of travel time, weighted costs of use and availability. The automation of driving, expressed as the share of highly and fully automated vehicles in the fleet, is influencing all three key factors via different cause-effect-chains and feedback loops. In SAFiP we identified four key impact sources: automated and remote parking, road capacity and travel speed, value of in-vehicle time and widening the range of users. Sensitivity tests for each of the impact sources have been carried out. Widening the range of users has the highest impact on a national level, potentially increasing car kilometers by about 17 percent in 2050. Remote parking increases car kilometers by about 5 percent in total, ranging from about 1 percent in peripheral districts to about 17 percent in Vienna.


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*Keywords:* Automated driving, System dynamics, Impact assessment

## 1. Rationale

Increasing digitalization and automation is expected to significantly change the transport system, mobility and settlement structures. A decade ago automated, self-driving vehicles were nothing more than an unrealistic (boyhood) dream in science fiction movies and books. But today the concept of highly and fully automated vehicles (AVs) is rapidly becoming a reality, with a series of real-world trial applications underway. The authors and their institutions have been and are involved in several research projects analyzing potential impacts of automated driving. The results presented in this paper stem from these projects. Hence, the spatial focus is on Austria and UK.

In Austria an action plan for automated mobility was published by the Federal Ministry for Transport, Innovation and Technology in 2016 (BMVIT, 2016). A regulatory framework, to enable the testing of specific use cases of automated vehicles on public roads, was defined (BMVIT, no date) and a national contact point for automated mobility was installed (AustriaTech, no date). Based on the use cases of the action plan, a Directive on Automated Driving was issued, setting the legal framework for tests on public roads (Zankl and Rehrl, 2018). At the end of 2016 Salzburg Research was granted permission to test self-driving shuttle buses in accordance with the directive AutomatFahrV (Austrian Federal Law Gazette II No. 402/2016). In April 2017 Salzburg Research was granted a license for testing a Navya Tech self-driving shuttlebus on public roads (Zankl and Rehrl, 2018). The final report documenting the results of the test phase was published in September 2018 (Zankl and Rehrl, 2018). In 2018 a follow up project named "Digibus® Austria" was started (Digibus® Austria, no date). "Digibus® Austria" is a flagship project funded by the Austrian Research Promotion Agency FFG and the Federal Ministry of Transport, Innovation and Technology within the framework of the "Future Mobility" funding scheme. The goal is to research and test methods, technologies and models for proofing a reliable and traffic-safe operation of automated shuttles on open roads in mixed traffic in a regional driving environment on automated driving level 3 ("Conditional Automation") and creating foundations for automation level 4 ("High Automation").

In the UK the government has invested heavily in autonomous vehicle trials since 2015 when it first published a code of practice for trialing automated vehicles which was recently updated (C-CAV, 2019). This included supporting three large trials of technology. The largest project being the AutoDrive project which successfully demonstrated the use of both autonomous vehicles in Coventry based on laps of the city center ring road and autonomous "pods" in Milton Keynes which move among pedestrians off road at a much slower pace (UK Autodrive, 2019). More recently, the UK government has announced more funding and investment to meet their goal of autonomous vehicles on UK roads by 2021 (GOV.UK, 2019). The objectives of the UK government are to strengthen guidelines on trial safety and transparency, seek to cement the position as a world leader in automated vehicle trials and to develop a process to help support advanced trials.

Most government plans and industry predictions expect a stepwise path towards high and full automation of private and public transport vehicles starting from the early to mid 2020s onwards (BMVIT, 2018; SYSTRA, 2018; ERTRAC, 2019). Nevertheless, there is still a high level of uncertainty in which form and to what extent automated vehicles will enter the market. Will fully automated private cars be the dominant form of mobility in the future? Or will automation come in combination with a switch towards car and ride sharing services? To what extent will automation be used to close the gap in the first and last mile of public transport? Furthermore, there are ongoing discussions concerning net effects of positive and negative aspects related to automation.

## 2. Background

The EU funded project CityMobil (Towards Advanced Road Transport for the Urban Environment) was one of first projects to address automated driving on a large scale (Benmimou *et al.*, 2009). The authors and their institutions have been involved in CityMobil, analyzing the potential impacts of different forms of automated driving. As part of this work, the System Dynamics based model MARS (Metropolitan Activity Relocation Simulator) was adapted to assess scenarios of automated driving in four European cities (Muir *et al.*, 2008). The scenarios included privately owned automated vehicles and automated vehicles in public transport. Simulations demonstrated that automated vehicles integrated into public transport have a potential to reduce car kilometers travelled and improve carbon footprint even without changes in propulsion technology. On the contrary, privately owned automated vehicles lead to an increase in car kilometers travelled. Unless propulsion technology is changed, this results in an increased carbon footprint.

While the focus of CityMobil was on the urban scale, the nationally funded Austrian project Shared Autonomy (Potential Effects of the Take-up of Automated Vehicles in Rural Areas – own translation) focused on rural areas (Haider and Klementschitz, 2017; Klementschitz *et al.*, 2018). The findings of Shared Autonomy show potential contributions of automated cars to improve the environmental situation and social inclusion in rural areas. These effects are however dependent on future use cases of the new technology and will only materialize if implemented in form of shared mobility rather than privately owned cars.

Finally, the recently finished nationally funded Austrian project SAFiP (System Scenarios Automated Driving in Personal Mobility – own translation) takes a look at the national territory of Austria (Pfaffenbichler and Emberger, 2019; Soteropoulos *et al.*, 2019). SAFiP was based on a multi-methodical approach of scenario technics, forecasting and backcasting embedded in a dialogue with experts and stakeholders from politics, administration, science, industry and civil society. Scenarios for personal mobility in Austria were developed, which describe the transport system in terms of multiple future pictures while anticipating the possibilities and developments in the field of automated transport. On this basis, the spectrum of transport-relevant impacts was quantified, requirements for various policy areas (R&D policy, transport policy, spatial planning, etc.) were developed and concrete further instruments and measures were identified. A revised and significantly modified nationwide version of the MARS model was employed to estimate the transport related effects of the different scenarios.

## 3. Method

The relationship between vehicle automation, travel demand and environmental effects consists of a multitude of complex cause-effect-chains. The toolbox of System Dynamics offers appropriate methods to tackle such complexities. In a first step, Causal Loop Diagrams were used to analyze and discuss relevant cause-effect-chains and resulting potential impacts (section 3.1). The results of the qualitative analysis were used to adapt different existing Stock-Flow-Models. An existing MARS model of for the city of Leeds was used for first tests of the quantification of the identified cause-effect-chains (May *et al.*, 2020). These first experiences and results were used to modify a national Austrian version of MARS (section 3.2). This modified Stock-Flow-Model was then used for a quantitative impact assessment in the SAFiP project. Additionally, sensitivity analysis in form of Monte-Carlo-Simulations was employed to tackle the high level of uncertainty concerning key factors (section 3.3).

While both models have the ability to assess potential effects of private automated vehicles, automated car and ride sharing as well as automated first and last mile public transport, the results presented here focus on the Austrian case study and the analysis of single elements associated with automated private.

### *3.1. Causal Loop Diagrams*

As part of the Austrian national project SAFiP (Pfaffenbichler and Emberger, 2019; Soteropoulos *et al.*, 2019), a detailed analysis of potential cause-effect-relations between the market take up of highly automated vehicles (i.e. level 4 and 5) and travel demand and environmental indicators was carried out. The analysis was based on the experience of the involved researchers, a literature review, discussions and feedback from experts. It served the development of an initial Causal Loop Diagram (CLD) which was then iteratively improved through internal project meetings with partners as well as feedback from experts at national and international conferences (Gühnemann *et al.*, 2018; Pfaffenbichler, 2018; Pfaffenbichler, Gühnemann and Emberger, 2019).

Figure 1 shows the final CLD identifying the connections between the market take up of automated private vehicles and the attractiveness and use of different means of transport. Similar diagrams have been developed for automated vehicles as part of car and ride sharing services and the first and last mile of public transport. For automated private cars the following five core elements and effects have been identified: diffusion of automated vehicles (1), remote parking (2), road capacity effects influencing average speed (3), value of in-vehicle time (4) and access for new user groups (5). The elements (3) road capacity and average speed and (4) in-vehicle time are analyzed in more detail in section 3.3.

**(1) Diffusion/market share of automated vehicles**: The diffusion of highly automated private vehicles is the starting point for the qualitative analysis. In the quantitative model the diffusion of automated vehicles is not modelled internally but rather a scenario input. The market take up (*level of automation private car*) is affecting several other elements of the system description of mode choice and private car use.

**(2) Remote parking**: Highly automated vehicles will be able to park on their own. Passengers can drop off directly at their destination. The automation of private cars (*level of automation private car*) therefore has an influence on the distance to parking places (*access/egress time parking place*) and parking place searching (*parking place searching time*). The polarity of these two links is opposite. If there is a higher level automation in the car fleet, then *access/egress time parking place* and *parking place searching time* decrease. This means lower generalized costs of travel time and hence higher attractiveness and use of private cars.

**(3) Road capacity and average speed**: There are high expectations that highly automated vehicles will harmonize driving conditions and reduce congestion. Hence, the automation of private cars (*level of automation private car*) has an influence on in-vehicle time (*in vehicle time private car)*. The polarity of this link is opposite. If there is a higher level of automation in the car fleet, then *in vehicle time private car* will decrease. This results in lower generalized costs of travel time and hence higher attractiveness and use of private cars.

**(4) Value of in-vehicle time**: A higher level of automation also has the potential to change the perception of in-vehicle time (*weighting in vehicle time private car*). Liberated from the driving task passengers can use the in-vehicle time for more pleasant and/or productive activities. The polarity of this link is opposite. If there is a higher level of automation in the car fleet, then *weighting in vehicle time private car* will decrease. This results again in lower generalized costs of travel time and hence higher attractiveness and use of private cars.

**(5) New user groups**: It is expected that the use of fully automated cars does not require a driver's license. Hence the availability of private cars for user groups without a driver license (*availability private car*) is increased. More people have access to private car and its attractiveness and use increases.

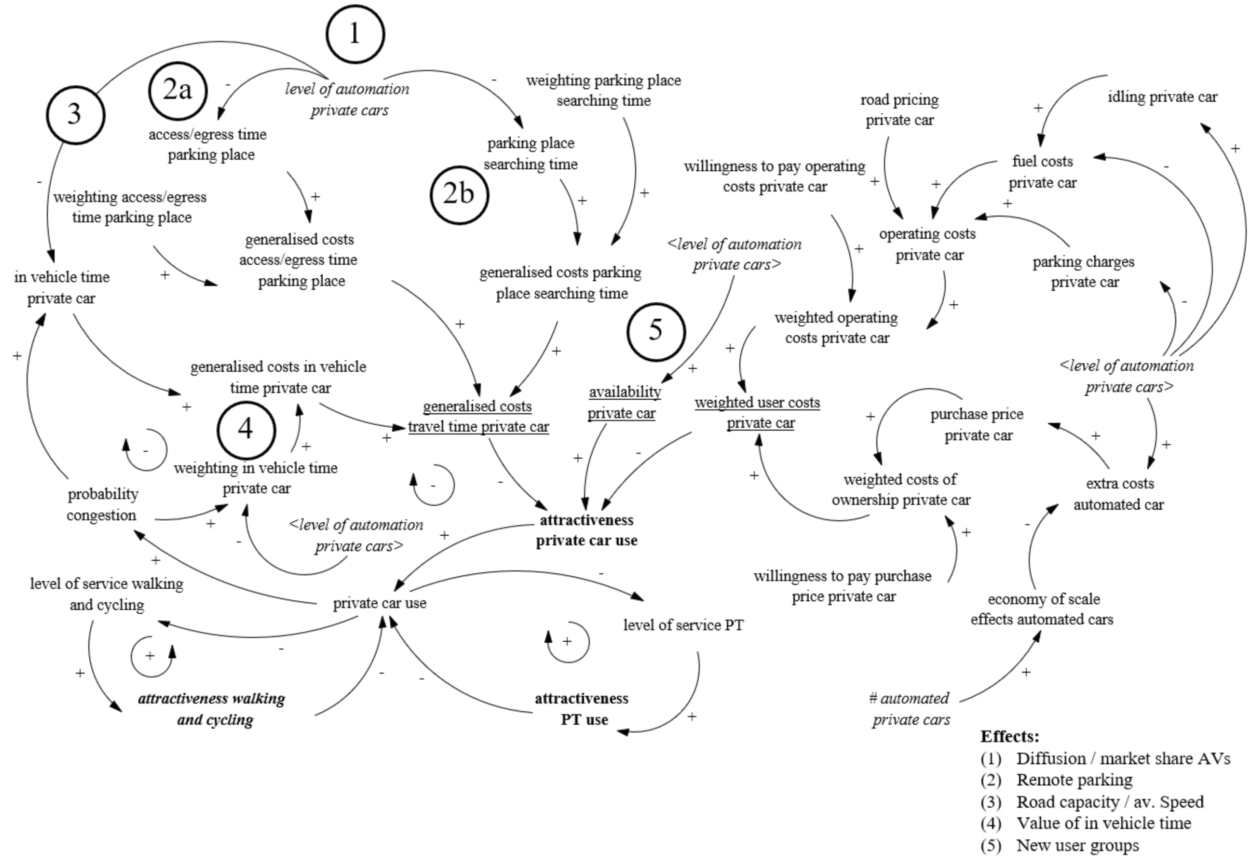


Fig. 1. Causal Loop Diagram – effects of the market take up of highly automated private cars.

**Other effects:** Automated cars are, at least in the short term, expensive. Automated cars hence increase investment costs for owning a car (*extra costs automated car*). Thus, costs of ownership are increased and hence attractiveness and use are decreased due to automation. Fully automated cars can avoid parking charges by driving to more distant parking places which are free of charge or they can idle until the passenger returns. Thus, parking costs (*parking charges private car*) can be reduced. More harmonized traffic can reduce fuel consumption and costs (*fuel costs private car*). On the other hand idling cars (*idling private car*) can increase fuel consumption and costs. If the number of automated cars increases (*# automated private cars*) economy of scale effects (*economy of scale effects automated cars*) come into effect and automated cars will become cheaper.

### *3.2. Stock-Flow-Model*

The quantitative analysis was carried out using a modified version of the system dynamics model MARS, which is an integrated transport and land use model developed to explore policies and scenarios at a macroscopic level (Pfaffenbichler, 2008, 2011). The MARS-SAFiP model is based on a previous version of MARS developed for the Environment Agency Austria (Krutzler *et al.*, 2017) and covers the whole area of Austria subdivided into 120 districts. The development and distribution of the Austrian population and employment is based on the forecasts made by the Austrian Conference on Spatial Planning (Hanika, 2010a, 2010b; Kytir, Biffl and Wisbauer, 2010). The development of the car fleet and its electrification follows the scenario WEM (With Existing Measures) of the Environment Agency's Energy and Greenhouse Gas Scenarios for 2030 and 2050 (Krutzler *et al.*, 2017). In 2050 about two thirds of the private cars are expected to have battery electric propulsion. The nominal price for fossil fuel at the pump is assumed to grow by about 30% until 2050. At the same time household income is assumed to grow by about 50%, resulting in a decrease of real fossil fuel prices. The price for electricity is assumed to grow by about 95% until 2050.

Due to restricted resources, it was not possible to model the market take up of level 4 and 5 cars internally in MARS. Instead, market share data from literature, e.g. (Fagnant and Kockelman, 2015; McKinsey & Company, 2016; Busch *et al.*, 2017; Krail *et al.*, 2019), are used as scenario variables which are then fed into a stock-flow-model to calculate the respective fleet shares. For the tests presented here, market take up follows the “high disruption scenario” of a McKinsey study (McKinsey & Company, 2016). This scenario results in a fleet share of about 90% level 4 and 5 cars in 2050.

In the SAFiP version of MARS a high level representation of the model (a Vensim® “view”) concentrating all elements that are influenced by the market take up of automated vehicles was created (Figure 2). This new structure facilitates the definition of a wide range of potential future scenarios of vehicle automation. The numbered circles refer to the same five core elements and effects as mentioned in the previous section 3.1. Elements with the extension “xls” in their name indicate parameters and scenario definition variables which are imported from Microsoft Excel® data files.

The definition of scenarios for the effects (2) to (5) consist of a switch to turn the single effect on and off and a variable to define the magnitude of the effect. In some cases, the latter has also a spatial component, e.g. concerning the effect of remote parking. The effect of automated private cars concerning the perception of in-vehicle time (4) is e.g. modelled as follows: The road network in the model MARS-SAFiP is differentiated into three categories: urban roads, rural roads and highways. The variable *scenario automated cars in vehicle time xls* serves to switch the effect on and off. The model user can define whether the perception of in-vehicle time is affected not at all, on highways only, on highways and rural roads or an all roads. The variable *scenario automated cars delta perception in vehicle time xls* defines the magnitude of the effect. The user has the possibility to assign different values to level 4 and level 5 cars. In accordance with (Wadud, MacKenzie and Leiby, 2016) the potential range is limited to -5% to -50%.

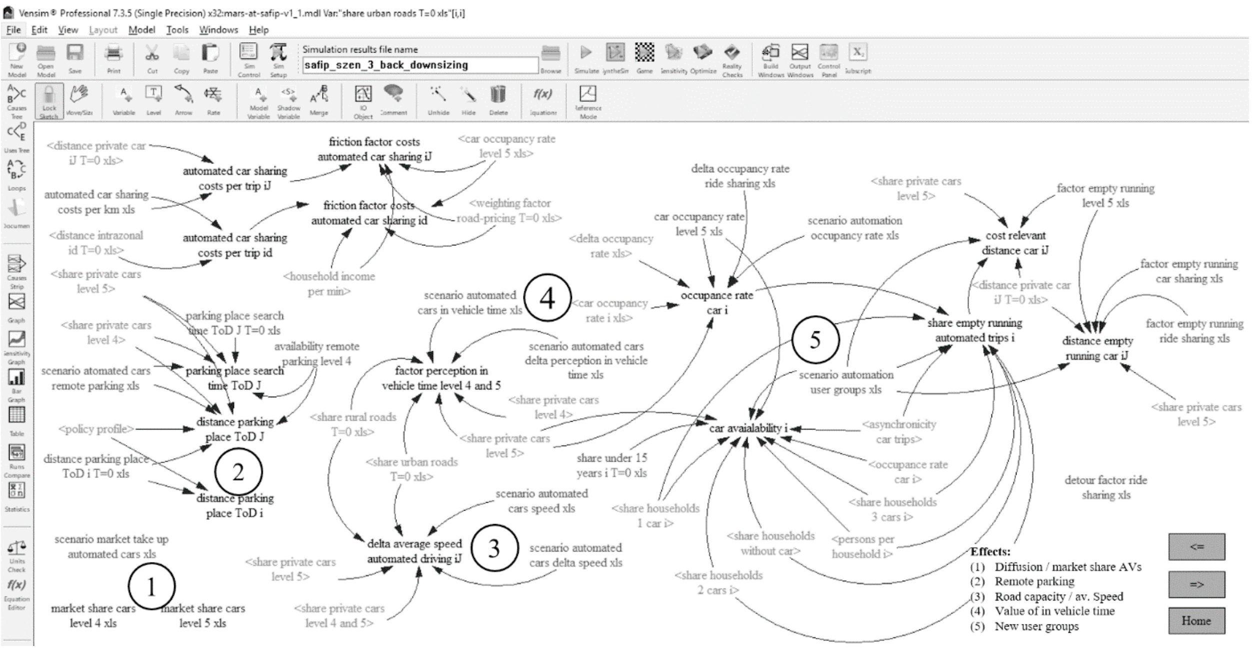


Fig. 2. Screenshot of the view “Automated driving” of model version MARS-SAFiP v1.1.

### 3.3. Sensitivity Analysis

Monte Carlo multivariate sensitivity works by sampling a set of numbers from within bounded domains. To perform one multivariate test, the distribution for each parameter specified is sampled, and the resulting values used in a simulation. A random nominal distribution was used in the tests documented below. This requires maximum and minimum bounds as well as a mean and standard deviation to be specified. The number of simulations was set to be 200.

**Value of in-vehicle time**: One of the major uncertainties is how automated driving affects the value of in-vehicle time. The variation of values reported in the available literature is quite large. (Wadud, MacKenzie and Leiby, 2016) report a range of -5% to -50%. A German stated choice experiment reports about -55% for low and medium income and -42% for high income groups (Kolarova *et al.*, 2018). For the sensitivity testing it was assumed that the effect on value of time matches a normal distribution defined by the following values: mean -30%, minimum -50%, maximum -5% and standard deviation +/- 10%.

Figure 3 shows the results of the abovementioned Monte Carlo simulations for the Austrian wide car kilometers driven per year. In the business as usual scenario (BAU) without a significant market take up above level 3 yearly kilometers traveled increases from about 62 billion kilometers in 2018 to about 78 billion kilometers in 2050 (black line with diamonds). The main driver for this development is population growth. In 2050 a reduction of the *value of in vehicle time* effect by the mean value of -30% results in an increase of car kilometers traveled of about +2.6% relative to BAU or in absolute terms about 80 billion kilometers. The median increase of car kilometers driven in 2050 is about +3.8% relative to BAU or in absolute terms about 81 billion kilometers (white line in Figure 3). The 50% confidence interval ranges from about +3.1% to +4.3% (dark grey area). The 95% confidence interval ranges from about +1.6% to +5.3% (light grey area).

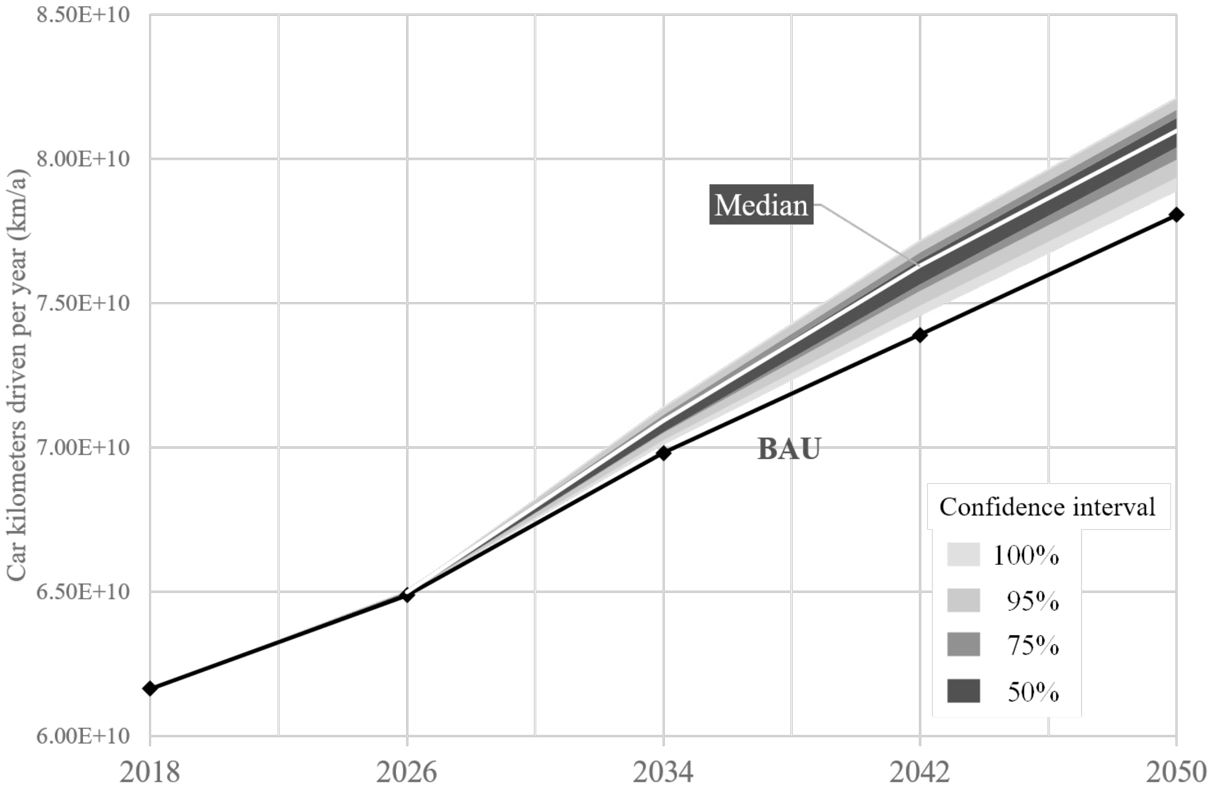


Fig. 3. Confidence interval car kilometers traveled per year – results Monte Carlo simulation value of in-vehicle time.

**Average speed off-peak**: An Austrian study concluded that in periods with low traffic volumes automated vehicles will be slower than conventional ones (Gruber *et al.*, 2018). The reason is that according to current legislation automated vehicles have to follow speed limits strictly and need to choose their speed according to their visibility range. An aggregation of the results for off peak travel speed by road category resulted in the following values: urban roads -7%, rural roads -5% and highways -12% (Pfaffenbichler and Emberger, 2019). Nevertheless, the uncertainty concerning these results is high. Other researchers argue e.g. that higher safety standards of automated vehicles would allow to raise or abolish existing speed limits (van den Berg and Verhoef, 2016; Wadud, MacKenzie and Leiby, 2016). Hence, it was decided to carry out a sensitivity analysis for the element off peak speed. It was assumed that the off-peak speed effect corresponds with the following normal distributions (urban/rural/highway): mean 7%/-5%/-12%, minimum -5%/-10%/-14%, maximum +14%/+14%/+20% and standard deviation +/-2% (all).

Figure 4 shows the results of the abovementioned Monte Carlo simulations for the Austrian wide car kilometers driven per year. In the business as usual scenario (BAU) without a significant market take up above level 3 yearly kilometers traveled increases from about 62 billion kilometers in 2018 to about 78 billion kilometers in 2050 (light grey line with asterisk). In 2050 the off-peak *capacity/speed* effect for the standard values of -7% (urban roads), -5% (rural roads) and 12% (highways) results in a decrease of the car kilometers of about -2.2% relative to BAU or in absolute terms about 76 billion kilometers. The median value for the increase of car kilometers driven in 2050 is about -0.3% relative to BAU (white line in Figure 4). The 50% confidence interval ranges from about -2.0% to +1.3% (dark grey area). The 95% confidence interval ranges from about -4.1% to +3.6% (light grey area).

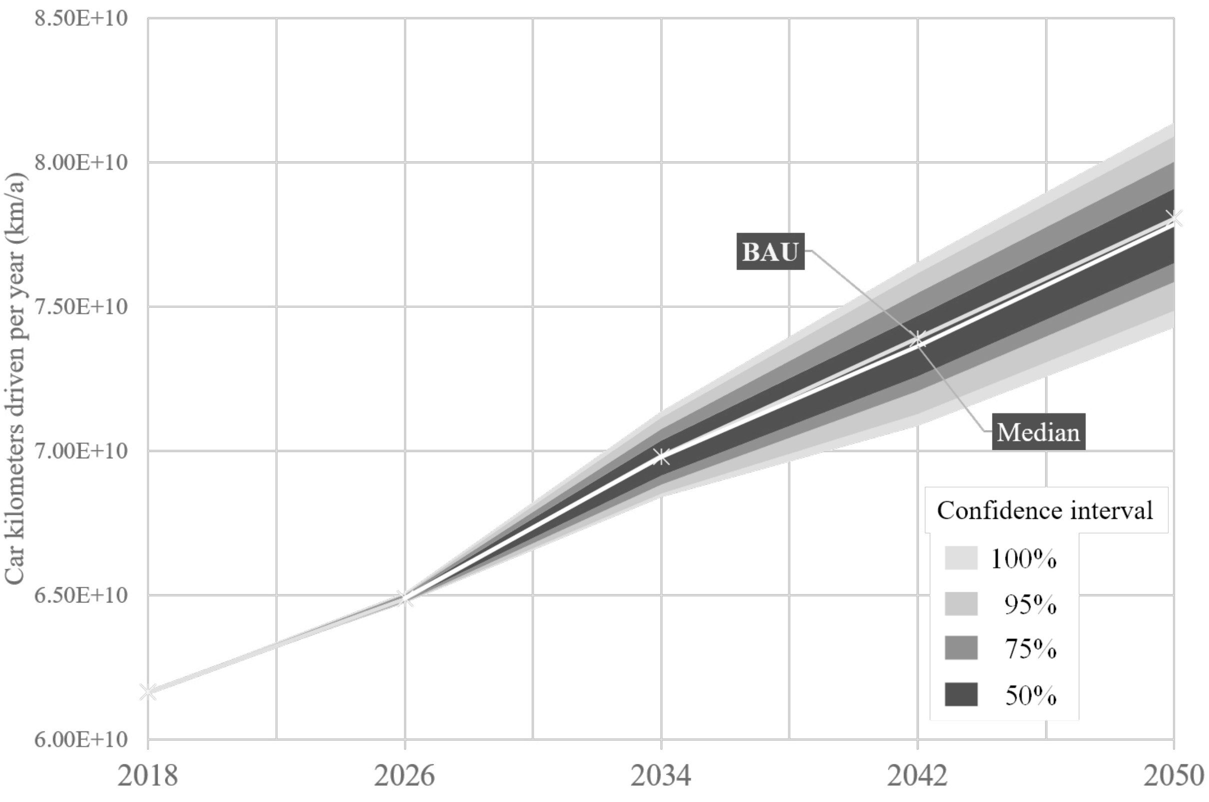


Fig. 4. Confidence interval car kilometers traveled per year – results Monte Carlo simulation value of average travel speed off peak.

## 4. Findings, results

The key factors, influencing mode choice and travel demand, are generalized costs of travel time, weighted costs of use and availability. The automation of driving, expressed as the share of highly and fully automated vehicles in the fleet of private cars, is influencing all three key factors via different cause-effect-chains and feedback loops. In

SAFiP four key impact sources were identified: automated and remote parking, road capacity and travel speed, value of in-vehicle time and widening the range of users (section 3.1). Automated and remote parking e.g. produces the following cause-effect-chain: Highly automated vehicles can park on their own, reducing or even avoiding the necessity to search for appropriate parking places. If there is a higher level of automation then parking place searching time decreases. This means lower generalized costs of travel time and hence higher attractiveness and use of private cars, resulting in an increase in car kilometers travelled. The identified qualitative cause-effect-chains have been implemented in MARS versions of the city Leeds and the whole of Austria (section 3.2). In order to tackle uncertainties sensitivity tests for each of the abovementioned impact sources have been carried out (section 3.3).

Table 1 gives an overview of the independently simulated effects of the four single elements on kilometers driven by region. On a national level unlocking *new user groups* has the potential to increase car kilometers by about 17% in 2050. This is the single highest effect. The effect varies by region, ranging from +16% in Vienna to +21% in peripheral administrative districts. Differences are caused by differences in car ownership rates. While people without driving license are able to use automated vehicles, in a scenario based on automated private cars it is still necessary that there is a car available in the household. (Haider and Klementschitz, 2017) estimate that car ownership in peripheral regions would only slightly increase (less than 5%) but expect a strong increase of mileage per vehicle and share of empty trips due to a lack of possibilities to combine rides within families.

*Remote parking* has its highest effect in Vienna, where parking spaces are scarce while demand is high. The effect is lowest in peripheral administrative districts where detached houses with private parking spaces dominate. On average remote parking increases car kilometers by roughly 5%. The effect of changes in the *value of in vehicle time* is of the same order of magnitude. Although regional differences are less pronounced, ranging from about 4% in central administrative districts to about 9% in Vienna. In the present parameter setting the only element which reduces kilometers driven is *road capacity/speed*. The average effect is a reduction of about 2%, while regional differences are not very pronounced.

Table 1. Overview of the change in kilometers driven caused by the different elements of automated private cars relative to BAU by region in 2050.

| Region | Remote Parking | Road capacity / Speed | Value of in-vehicle time | New user groups |
|---|---|---|---|---|
| Vienna | +16.7% | -2.7% | +8.7% | +16.1% |
| Major cities (without Vienna) | +9.0% | -3.0% | +5.4% | +17.2% |
| Central administrative districts*) | +4.4% | -2.6% | +3.5% | +19.6% |
| Peripheral administrative districts*) | +1.4% | -1.6% | +5.8% | +21.0% |
| Austria | +4.5% | -2.1% | +5.1% | +16.8% |

*) Classification of the Austrian administrative districts. If less than 73 per cent of the population has access to a supra-regional center by car and public transport then the district is classified as periphery otherwise as central district.

All individual triggers, except speed during off peak, increase kilometers travelled by private car compared with the business as usual scenario. The largest effects arising from unlocking new user groups. The combination of triggers has a synergetic effect. The increases in car kilometers travelled suggest that, other things equal, the environment will be adversely affected. Results depend on input assumptions, but they suggest that it is important to gain a clearer understanding of the likely scale of each of the four factors: impacts on capacity, parking and access time, in vehicle values of time and the extent to which current non-drivers will be permitted to use cars. They confirm that the introduction of automated cars is likely to have a deleterious effect on the environment and policy interventions to mitigate this effect are necessary.

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