Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

The potential impacts of automated cars on urban transport: an exploratory analysis

Anthony D May [a] *, Simon Shepherd [a], and Paul Pfaffenbichler [b] and Günter Emberger [c]

[a] *Institute for Transport Studies, University of Leeds, Leeds, LS2 9JT, United Kingdom*
[b] *Institute for Transport Studies, University of Natural Ressources and Life Sciences, Vienna, 1190, Peter Jordan Strasse 82, Austria*
[c] *Research Center for Transport Planning and Traffic Engineering, University of Technology Vienna Vienna, 1040, Gusshausstrasse 30/2, Austria*

Abstract

Objective The concept of automated cars is rapidly becoming a reality, with a series of real world trial applications underway, and government predictions that automation will be introduced in the early 2020s. Yet there has still been very little analysis of the impacts of such developments on the performance of urban transport systems. These impacts are potentially complex. On the positive side, automation has the potential to increase road capacity, make driving available to more people, and reduce accidents and emissions. On the negative side, it could attract users away from public transport, walking and cycling, substantially increase traffic levels and stimulate urban sprawl. These impacts cannot currently be measured empirically and, by the time that they can, it will be too late to change the implementation model to rectify any resulting problems. Predictive assessments are therefore needed. The objective of this paper is to consider the possible impacts of automated vehicles, to predict their effects on the urban land use and transport system, and to discuss the policy implications. We focus specifically on automation of the car fleet, and do not consider the potential of automation of public transport or freight vehicles.
Methods We consider the current literature on the range of attributes of automated vehicles which might affect transport and land use patterns, and suggest potential outcomes for each over the period to 2050. These attributes include the proportion of automated vehicles in the car fleet, whether automated vehicles are privately purchased or publicly shared, the impacts of automation on network capacity, the reduced need to pay for and walk from parking places, the potential reduction in the value of in-vehicle time and the ability of those who cannot currently drive to use cars. We represent these attributes in an expanded causal link diagram of the urban land use and transport system, import those causal links into the MARS systems dynamics model, and test the impacts in a set of ten scenarios using an updated MARS model of Leeds.
Results Based on our input assumptions, we find that kilometres travelled by car in 2050 could be over 50% higher than in the business as usual scenario. Public transport use could fall by 18%, threatening accessibility for those dependent on it, while walking and cycling could fall by 13%, reducing their health benefits. Overall person-km would rise, suggesting a tendency to

* Corresponding author. Tel.: +44 (0)1904 621796.
E-mail address: A.D.May@its.leeds.ac.uk

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY

urban sprawl, which is confirmed in subsequent tests. A requirement that all automated cars are made available as shared vehicles could reduce these adverse impacts somewhat, but the effects appear to be sensitive to the charge per km which is imposed.
Discussion These results demonstrate the importance of understanding the scale of systems response to each of the attributes which we have considered. In terms of policy, it will clearly be important to manage the way in which automated cars are introduced into urban areas, if they are not to lead to a worsening of the urban environment, accessibility and health. A requirement to make all such vehicles part of shared fleets offers one way forward, but more work is needed to understand the way in which use of such fleets should be charged.

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.

Keywords: autonomous vehicles; urban transport; modal choice; land use

1. Introduction

The concept of vehicle automation has been promoted for several decades, but has now approached reality. It is generally accepted that there are potentially six levels of automation: 0 No Automation, 1 Driver Assistance, 2 Partial Automation, 3 Conditional Automation, 4 High Automation and 5 Full Automation (SAE International, 2016). Vehicles of levels 1-3 are already available in the market, and offer drivers greater safety and comfort and a simpler driving task. Vehicles of types 4 and 5 are in production, and governments anticipate that they will be in operation on public roads early in the next decade. For example, Daimler recently announced the development of prototypes for levels 4 and 5 by 2020, BMW has announced it would offer automated vehicles at level 4 and 5 from 2021 and Tesla has declared that it can offer level 4 and 5 today, if they are legally permitted. The UK government has a commitment to have level 4 and 5 vehicles operational on public roads by 2021 (HMG, 2017). In 2016 the Austrian government published an action plan for automated driving (BMVIT 2016). The main objective of the action plan was to create the legal framework to facilitate Austrian test beds for automated driving.

The stimulus for these developments has been largely technology-led, with governments using their regulatory and financial support to achieve industrial competitive advantage. Benefits to the public are typically presented as increasing safety and driving comfort, enabling those who cannot currently drive to use private vehicles, and improvements in the capacity of the road network (BMVIT, 2016). However, full automation could potentially lead to a much wider range of impacts, whose benefits to society are at best uncertain (Hensher, 2018), Wadud et al, 2016). If the driving task is removed, time spent driving can be used for other purposes, leading to a reduction in the implicit value of travelling time. This in turn could make private car use more attractive than public transport, walking and cycling, resulting in substantial changes in modal shares, and potentially encouraging urban sprawl. If, as envisaged, empty vehicles can return autonomously to low cost suburban parking areas, this could accentuate the pressures for urban sprawl while making city centre space available for more intensive development (Zakharenko, 2016); moreover it would add substantially to traffic flow, thus reducing the benefits of capacity enhancement.

Milakis et al (2018) report a survey of 17 experts' views on these likely impacts using the Q-method. They summarise their respondents' viewpoints as being:

A. that automated vehicles will lead to induced travel demand, offsetting their accessibility benefits;

B. that automated vehicles will induce both city centre densification and urban sprawl;

C. that automated vehicles will bring user benefits, but only for those able to afford them.

While these viewpoints are in some ways inconsistent, the respondents were consistent in their views that automated vehicles would increase comfort and safety, but at the same time generate increased travel, and overall have very limited benefits for either individuals or society. Hensher (2018), Milakis et al (2018) and Wadud (2016) all conclude that the resulting impacts on sustainability, as measured through changes in congestion, accessibility, equity and energy consumption, are likely to be negative.

The scale of these impacts will depend also on whether automated vehicles are sold to individuals, as conventional manufacturers would prefer, or offered as shared vehicles as promoted by ICT companies and public transport bodies

(ITF, 2015, UITP, 2017, Hensher, 2018). Shared vehicles are typically used more efficiently, since the adoption of a charge at the point of use makes their marginal use less attractive than that for private cars.

Despite these potentially significantly damaging societal impacts of automation, there has been little analysis of the potential impacts of automation on urban land use and transport, or of the strategies which cities should adopt to mitigate any adverse impacts. In some ways this is not surprising; prior to their full scale introduction it is not possible to obtain empirical evidence on behavioural responses to them. Instead, predictive models are needed, but conventional models typically do not represent automated vehicles as a mode or reflect the land use consequences.

In this paper we aim to remedy this by using a systems dynamics model speculatively to assess the possible impacts over time of the introduction of automated cars under different governance regimes. The systems dynamics model which we use, MARS, has been validated for the city of Leeds, UK, and enables us to input possible behavioural responses to changes in market shares, shared or individual ownership, capacity, parking options, and in-vehicle travel time values, and hence to predict the range of possible impacts on modal shares, land use and congestion. We focus solely on full (levels 4 and 5) automation of private cars, and do not consider the potential impacts of parallel automation of public transport or freight.

In Section 2 of this paper we review the literature on possible market penetration of automated vehicles, the ownership and sharing options, possible user and systems responses, and previous attempts at analysis. In Section 3 we describe our analytical approach. Section 4 outlines the range of assumptions that we have tested. In Section 5 we present the results of our speculative tests for Leeds. Finally we draw conclusions and discuss the policy and governance implications.

2. A review of the literature

2.1. Potential market penetration of level 4 and 5 vehicles

Nieuwenhuijsen et al (2018) offer a detailed review of the literature on the potential take-up for each level of automation for cars, and their own detailed projections for the Netherlands. Earlier projections suggested that levels 1-3 might represent as much as 70% of the market for private cars by 2020 (Shladover, 1995, 2015; Underwood, 2014; Kyriakidis et al, 2015). There is little literature offering projections for level 4, but for level 5 the literature envisages market introduction from 2025, a 25% market share by 2035 and a 50% market share before 2050 (studies cited in Nieuwenhuijsen et al, 2018).

Nieuwenhuijsen et al (2018) use a simulation model to investigate likely market shares in a range of scenarios. They find that future market shares are highly uncertain, with a base case share for levels 4 and 5 of under 5% in 2050 without market stimuli. Conversely, they suggest that stimuli such as subsidising purchase, financial support for product development, knowledge transfer and fleet replacement policies could dramatically increase take-up of levels 4 and 5. Their “bloom conservative” scenario has levels 4 and 5 accounting for 15% market share by 2025 and 90% by 2050. Their “bloom progressive” scenario lifts these to 60% and 100% respectively. Separately, McKinsey estimate market shares for a “high disruption scenario” (McKinsey & Company 2016), in which levels 4 and 5 combined reach a market share of 100% by 2040. In a “low disruption scenario” levels 4 and 5 combined reach a market share of about a third by 2040.

2.2. Individual and shared ownership

Car clubs, often referred to as car sharing, in which vehicles are owned by a provider and used by individual club members for a fee, have been in operation for two decades, and now form a key element of the shared economy in mobility. There is ample evidence that they reduce the size of the vehicle fleet and that, by charging at the point of use, reduce the modal share for car use. As a result, road space is used more efficiently, and parking requirements are reduced. For example, in Bremen, 37% of car club members ceased to own a vehicle on joining, and because they are more intensively used, each car club car is estimated to have replaced 11 privately owned cars (Glotz-Richter, 2015). Steer Davies Gleave have been reviewing the impact of car clubs in London for several years. Their latest report (SDG, 2017) surveyed 4000 of the 193,500 members of six operators’ services. It found that each car club car replaced 10.5 privately owned cars, and that only 24% of car club members owned cars, as compared with 57% of all

London households. On average, car club members travelled 3035 miles per year by car, as compared with 6900 miles for all car owners. Car club vehicle occupancy averaged 2.6, as opposed to 1.6 for all cars; car club cars were more likely to be used for leisure and personal business, and less for commuting. Though not cited in the report, typical charges range from 0.31 €/min to 0.38 €/min (Car2go (2018); DriveNow, 2018). All costs for parking, refueling and insurance are included in these charges.

An initial study by the International Transport Forum (ITF, 2015) used an agent-based model of Lisbon to assess the potential of two, five and eight seat shared self-driving cars and shared taxis to replace all current travel by car, taxi and bus and, as an extension, by all public transport. It found that the number of cars in use could be reduced by around 90%, and the need for parking almost eliminated. Vehicle-km travelled in the peak would rise by 6% with trams and trains retained, and by 89% if they, too, were replaced. A subsequent Lisbon study (ITF, 2016) tested an option with shared mobility fleets of six seater shared taxis and eight and 16 seater minibuses. If these replaced all cars, taxis and buses, they were estimated to reduce the car fleet and parking needs by 97%, vehicle-km by 37% and carbon emissions by 34%. In considering the transition to wholly shared ownership, ITF tested options with private vehicle owners restricted to using their cars one, two or three days a week. They found that with private cars being used three days a week, there was no reduction in congestion, while limitation to two days a week reduced vehicle-km in the peak by 13%, thus largely removing congestion. A subsequent study in Helsinki (ITF, 2017) found that replacing cars, taxis and buses by shared mobility reduced vehicle-km by 23% and carbon emissions by 28%, while simply replacing cars and taxis had a greater impact, with vehicle-km falling by 33% and carbon emissions by 34%.

These studies demonstrate clearly that a shared economy model would be likely to reduce the size of the vehicle fleet, increase the intensity with which vehicles are used, and have the potential to reduce vehicle-km travelled. Automation would facilitate the operation of car clubs by enabling vehicles to be available where and when needed. The International Association of Public Transport (UITP) defines three different potential future scenarios of automated driving. In the first automated vehicles simply replace private cars. In the two others automated vehicles are used in shared fleets, which either compete with or are integrated with public transport (UITP, 2017). They argue that, while the first and second would increase vehicle-km travelled, the third should lead to a reduction. They also note the benefits of increased accessibility and reduced demand for parking which arise from a transition from the first to the second, and from the second to the third scenario.

2.3. Supply responses

Vehicle automation should in principle change the supply in several ways. The most significant would be a reduction in inter-vehicle headways, by removing the time required for the driver to react to the vehicle in front. This in turn should increase the capacity of the existing road network. However, the full effect would only be realised with full automation. The second impact would be through a reduction in accidents and near misses, which arise largely through human error. These have a more unpredictable impact on capacity, but their reduction should substantially reduce the variability of travel times in a network. The third impact would be on speed, which would depend on vehicle capabilities and system settings. Atkins (2016) illustrate the difficulties of predicting this change, and we have not attempted to consider it further here. The final impacts relate to parking. At present a significant proportion of peak traffic is due to searching for parking spaces; an automated vehicle should be able to identify an available parking space and travel straight to it. As an extension, it would no longer be necessary for the vehicle to remain parked at its user's destination. Shared vehicles would simply move on, empty, to collect their next user; privately owned vehicles could return empty to locations where parking is free. In both of these ways the need for parking in city centres should be much reduced, with on-street parking largely removed, thus further increasing road network capacity, and some off-street provision would become available for conversion to other uses.

Wadud et al (2016) explore the impacts of these supply responses on energy consumption. They also consider the impacts of automation on promoting the purchase of higher specification vehicles and, conversely, of vehicle downsizing given the reduced emphasis on crash protection. While these are relevant to energy consumption, they are unlikely significantly to affect capacity in urban areas. Muir et al (2008) conducted microsimulations of two road networks with different proportions of automated vehicles. They also developed a simple relationship between network capacity and the proportion of automated vehicles. If, for example, inter-vehicle headways for automated vehicles are two thirds those of standard vehicles, full automation would increase capacity by 50%, while a 40% fleet share would only increase capacity by 8%, and a 50% fleet share by 12.5%. Atkins (2016) conducted a more detailed simulation of impacts on urban and interurban traffic for the UK Department for Transport. They quote other analyses which suggest a capacity increase for full automation of around 40%, but with little impact for fleet shares of under 40%. Their own simulations also take account of driving style, from cautious to aggressive, and produce results which are less sensitive to fleet share. Their urban simulation gives reductions in average journey time of 31% for full automation, and of 26% with a 50% fleet share.

2.4. Demand responses

The three principal triggers of changes in demand in response to automation are likely to be the impact of being able to use the time spent travelling for other purposes, the avoidance of time spent parking and walking to and from a final destination, and the potential for those who are not currently able to drive to use automated vehicles. As noted above, offering automated cars as shared vehicles with a charge at the point of use will also impact on demand, as will the potential for privately owned vehicles to return empty to low cost parking spaces.

Wadud et al (2016) review the limited literature on possible changes in the value of in-vehicle time, which are largely based on comparison of car drivers with car passengers and with rail users. On this basis they suggest that the value of time might fall by between 5% and 50%. MacKenzie et al (2016) suggest that the overall cost of using an autonomous vehicle might be as much as 80% lower than that for a conventional car. Wadud et al (2016) also explore the impact of expanding the user base among the elderly and infirm. On that basis they suggest that car use might increase by between 2% and 10% if these groups used cars as fully as other adults. As noted in Section 2.2 above, offering automated cars as shared vehicles might have a further impact on vehicle-km travelled. We have found no estimates of the effects of reduced time spent parking or empty running to outer suburban parking spaces.

2.5. Previous assessments of systems responses

While the agent-based model used by ITF was able to reflect the use of alternative vehicles for existing journeys, it did not attempt to assess the longer term impacts on patterns of travel and land use. However, the earlier CityMobil project had attempted to assess the long-term impacts of a range of automated technologies (Shepherd, et al., 2008). The study used the dynamic land use-transport interaction model MARS (Metropolitan Activity Relocation Simulator) (Pfaffenbichler, et al., 2008) in four case study cities: Madrid, Trondheim, Gateshead and Vienna. The new automated technologies which were modelled in MARS were termed cybercars, Personal Rapid Transit (PRT), automated buses and dual mode vehicles. Of these, cybercars, defined as driverless vehicles that operate in streets with mixed traffic, were closest to the automated vehicles considered here. They were tested in two application scenarios: as an enhancement to the inner city public transport system, and as a feeder to outer suburban public transport. Dual mode vehicles were assumed to be able to operate both conventionally and as automated vehicles with lower headways. This effect was incorporated into the model by assuming that the capacity of the entire road network increased incrementally year on year, so that in year 2035, with an assumed penetration rate of 40% of dual mode vehicles, the total capacity would be 8% greater than in 2005 (Muir, et al., 2008). All four new technologies were tested under medium and high growth context scenarios and both with and without complementary measures.

Given the limited scale of the proposed applications, city-wide impacts were small, but more dramatic impacts were predicted at a local level (Shepherd and Muir, 2009). While these local impacts varied with system application and city, the most significant impacts were for cyber cars as feeders to public transport. Conventional car use was seen to fall locally by between 1% (Trondheim and Vienna) and 8% (for Gateshead and Madrid). This reduction in car use was accompanied by a more substantial reduction in the use of slow modes (ranging from 3% in Trondheim to 45% in Madrid) and an increase in overall public transport use.

3. The analytical approach

3.1. The approach to modelling

Given the earlier study of longer term impacts, we elected to use the MARS model to conduct the quantitative tests reported in this paper. MARS is a dynamic, integrated Land Use and Transport Interaction (LUTI) model. It includes a transport model which simulates the travel behaviour of the population related to their housing and workplace location, a housing development model, a household location choice model, a workplace development model, a workplace location choice model, and a fuel consumption and emission model. All these models are interconnected with each other via accessibility, spatial distribution of origins and destinations and land availability and price. The number of trips in MARS is determined assuming a constant travel time budget whereby the total time spent commuting is subtracted from the total time budget for the population and assigned to other trips. This effect may be significant once we include lower values of time associated with automated vehicles. MARS is implemented in Vensim® DSS with Microsoft Excel® as data user interface. More detailed documentation of the model MARS can be found in (Pfaffenbichler, et al., 2008), (Pfaffenbichler, et al., 2010) and (Pfaffenbichler, 2011).

The experience with modelling automated vehicle technologies in the CityMobil project made MARS an excellent starting point. Nevertheless, new developments in technology and new forms of mobility required significant revisions to the structure of the model. The first step in this process was the development of detailed causal loop diagrams identifying the connections between automated vehicles and the attractiveness and use of different means of transport. Figure 1 shows the resulting causal loop diagram for the effects of introducing automated private cars.

The automation of private cars (*level of automisation private car*) has an influence on the distance to parking places (*access/egress time parking place*), parking place searching (*parking place searching time*) and in vehicle time (*in vehicle time private car)*. Highly automated vehicles can park on their own and reduce congestion. Hence the polarity of these links is opposite. If there is a higher level of automation then *access/egress time parking place*, *parking place searching time* and *in vehicle time private car* decrease. This means lower generalised costs of travel time and hence higher attractiveness and use of private cars. A higher level of automation also has the potential to influence 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 other activities.

The use of fully automated cars does not require a driver licence. Hence the availability of private cars for user groups without a driver licence (*availability private car*) is increased. More people have access to private cars and their attractiveness and use increases.

Automated cars are, at least in the short term, expensive. Automated cars hence increase the capital cost of owning a car (*extra costs automated car*). Thus costs of ownership are increased and hence attractiveness and use are reduced due to automation. Fully automated cars can avoid charges for parking by driving to more distant parking places or they can idle until the passenger comes back. Thus parking costs (*parking charges private car*) can be reduced. More harmonised 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.

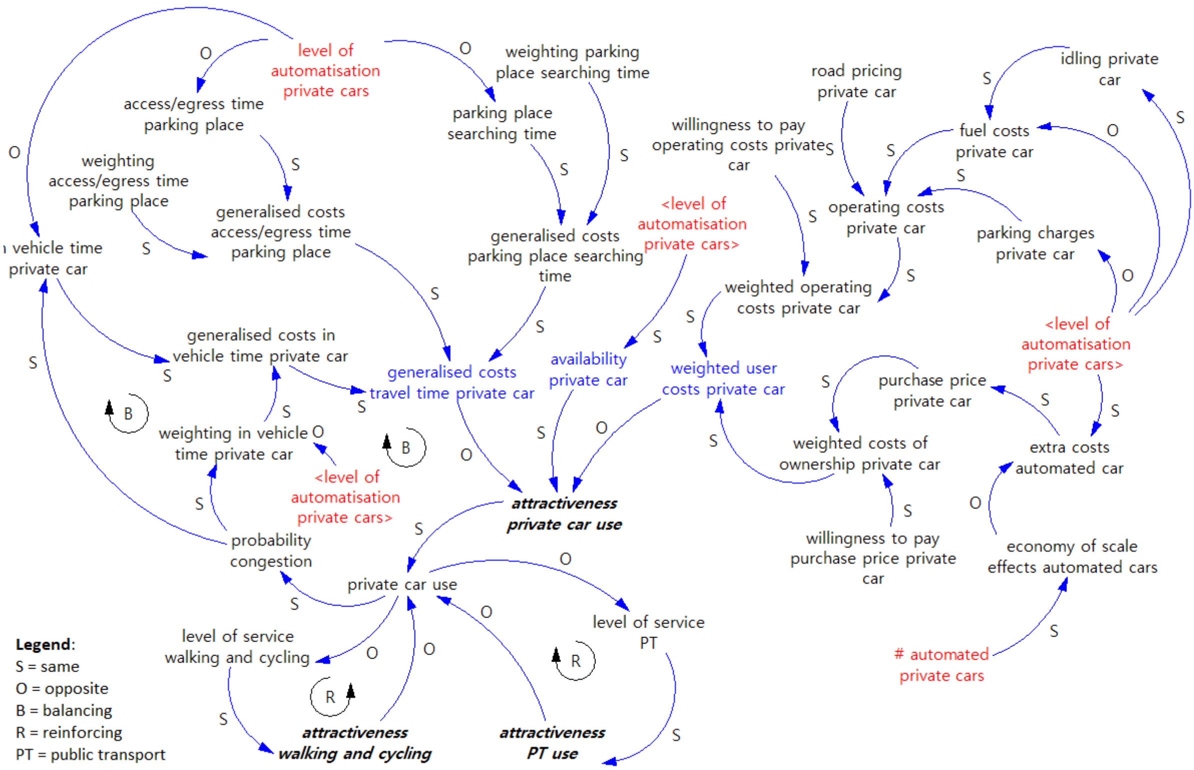

Fig. 1 Causal-loop diagram describing the effects of automated private cars

While we modified MARS to include all of these possible causal effects, the literature review demonstrates that they are not yet certain to arise, and that even if they do, their scale needs to be determined. We used our scenario testing to consider what appeared to us to be the most likely and significant impacts.

3.2 Indicator set to describe the performance of the tested scenarios

Land use und transport interaction (LUTI) models like MARS calculate in each simulation run a large number of indicators which are either zone related, such as number of inhabitants or work places per zone and year, or origin-destination (OD) related, such as the number of trips and travel time by each mode of transport between each pair of zones. For specific analyses these indicators can be further differentiated for various household types (e.g. low/high income and/or with/without access to cars), different time periods (peak and off-peak) and different trip purposes (work and non-work). It is thus important to choose an appropriate indicator set, which can be used to describe the overall system behaviour, the performance of the tested scenarios and the effect of input parameter variations. In this paper we focus on the impacts of automated vehicles on congestion, mode share distribution, the environment and urban sprawl. To be able to describe these impacts we have chosen to display the indicators listed in table 1 for each scenario. We use index values to compare each scenario in 2050 with the base in 2015 and with the business as usual scenario S0 in 2050.

The change in car- and person-kilometres are used to provide an indication of the impacts that the tested scenarios will have on car-dependency. These indicators are also proxies for total energy consumption, the total environmental impacts, for urban sprawl, space consumption and for safety issues. The more vehicle kilometres that are driven, the longer the distances become per trip and the more inhabitants use cars for their commuting and other trips. This will increase the dependency on motorised means of transport. Since we did no tests regarding alternative powertrains the total number of car-km can also be used as a proxy for greenhouse gas emissions. Further, the total car-km provide an indication for noise emissions, and can be used, when separated between traditional and automated vehicles, to estimate the number and severity of traffic accidents. The change in person-km provides a broad indication of the changes in accessibility, with an increase suggesting worsening accessibility and a tendency to urban sprawl and space consumption.

To assess how the different scenarios perform regarding congestion the indicator average travel speed in km/h is used. A faster average travel speed means that congestion is reduced, while on the other hand in the longer run this can lead to more car use, so careful interpretation of this indicator is necessary.

We have also used a more direct indicator of trends in urban land use, by considering changes in the distribution of population between the city centre, inner city and outer city as compared to 2015.

Table 1. Output indicators used to describe the impacts of the tested scenarios

Name of indicator	**Unit**
Travel	
Car-km	car km as an index compared to 2015 and index point change from S0 in 2050
Pkm-slow	person-km per capita per year by slow modes as an index compared to 2015 and index point change from S0 in 2050
Pkm-pt	person-km per capita per year by public transport as an index compared to 2015 and index point change from S0 in 2050
Pkm-car	person-km per capita per year by car as an index compared to 2015 and index point change from S0 in 2050
Pkm-total	total person-km per capita per year by all modes as an index compared to 2015 and index point change from S0 in 2050
Modal Split shares (absolute and index point changes)	
car	percentage in a given year and index point change from S0 in 2050
pt	percentage in a given year and index point change from S0 in 2050
slow	percentage in a given year and index point change from S0 in 2050
Car speed in km/h	km per hour in the peak in a given year
Residential distribution	percentage change in population in 2050 by comparison with S0, by area

4. The scenarios tested

As noted in the introduction, the lack of empirical evidence means that we are unable to provide precise estimates of the scale of the causal processes affecting the response of urban transport and land use systems to the introduction of automated vehicles. Instead we used the literature review above to categorise the variables which we consider in our MARS tests. These are listed below.

<u>Market and fleet share</u> As noted in Section 2.1, the estimates of market share for level 4 and 5 vehicles in 2025 and 2050 are themselves uncertain. It appears to us that it is most informative to assess the implications of the highest level of predicted growth in the market, since these will require an earlier policy response. We have therefore used McKinsey's predictions (McKinsey and Co, 2016) which show levels 4 and 5 combined reaching a 100% market share by 2040. Using a simple stock flow model translates this market share into a 2050 fleet share of about 90% for levels 4 and 5.

<u>Individual or shared ownership</u> To keep our analysis simple, we have conducted separate tests in which all cars are privately owned, and in which all cars are shared. For the latter we have assumed a transition from only private level 0-3 cars in 2015 to only shared level 4 and 5 vehicles by 2050. Base year data from the Leeds MARS model for distance and speed have been used to convert the time based charges mentioned in section 2.2 into vehicle-km based charges by origin-destination pair. Depending on vehicle size average charges range from €0.53 per vehicle-km to €0.65 per vehicle-km. We have assumed that shared use incurs a cost of €0.55 per vehicle-km, reflecting the lower end of this range, As the ITF studies have demonstrated, significantly fewer vehicles, and thus parking spaces, will be

required for shared ownership, resulting in public space being freed and potentially made available for walking and cycling. We have not attempted to assess the impact of this as yet.

Capacity The formula developed by Muir et al (2008) (see Section 2.3) was used to modify the way in which the MARS model represents network capacity. Since it produces results similar to other studies, we have used the same formulation, with capacity increasing in a non-linear way in response to increases in fleet share.

Parking search MARS assumes that, for automated vehicles, there is no need to search for a parking space or walk from it. Thus the travel time associated with parking at the destination is zero. It is possible to make similar assumptions for the origin, but we have omitted them in this analysis. We assume for simplicity that the car drives itself to a parking space with the same level of parking charge as at present. We have not made any allowance for the reduction in traffic flow as a result of the removal of the need to search for a parking space.

Remote parking If vehicles are privately owned, they could potentially return empty to base, where parking will be cheaper. We have not been able to reflect this in our current model, thus potentially underestimating the traffic generating effects of private ownership.

In-vehicle values of time As noted in Section 2, there is a wide range of estimates of the possible reduction in values of in-vehicle time resulting from the ability to use that time for other purposes. For simplicity, we have taken a mid-range value of a 50% reduction.

Widening the range of users We have assumed that every adult in households with an automated vehicle can potentially use that car. Thus the limitation that there has to be at least one person with a driving licence is removed. Since it is possible that licensing authorities might still impose conditions on private owners of automated vehicles, we have included a test in which this extension of use does not apply.

Other modes As noted in the introduction, we have assumed that public transport and freight operations remain unchanged. In practice they could be expected to benefit from automation, but the resulting impacts are beyond the scope of this study.

Our analysis above provides five variants for our test scenarios: ownership, capacity, parking search, value of time and widened access. For simplicity we have separated our tests into ones with private and with shared ownership, and tested each of the other factors on its own, and all applied together. This gives us a total of 10 scenarios for Leeds, as summarised in table 2.

Table 2. Dimensions of the scenarios tested.

Scenario	Market share Levels 4 & 5 cars	Ownership	Capacity	Parking search	In-veh VoT	Access for all	Scenario
0	Zero	Private	N	N	N	N	0
1	100% by 2040		Y	N	N	N	1
2			N	Y	N	N	2
3			N	N	Y	N	3
4			N	N	N	Y	4
5			Y	Y	Y	Y	5
6		Shared at € 0.55/km	Y	N	N	Y	6
7			N	Y	N	Y	7
8			N	N	Y	Y	8
9			Y	Y	Y	Y	9

5. Results

The share of AVs level 4 and 5 was modelled as a simple stock flow model converting market shares from the literature (McKinsey & Company 2016) into fleet composition. The development of the technology was exogenous as described above and so all scenarios have the same development over time for AV levels 4 and 5 as shown in Figure 2. It should be stressed that the access to this technology differs by scenario and is based on either sharing of privately owned vehicles within the household (S1-5) or full access to shared vehicles with a charge per km (S6-9). In the latter case this means that the percentage of the population with a car available in a zone increases to between 93% and 99%. This compares with availability as low as 34% in the off-peak without AV sharing options.

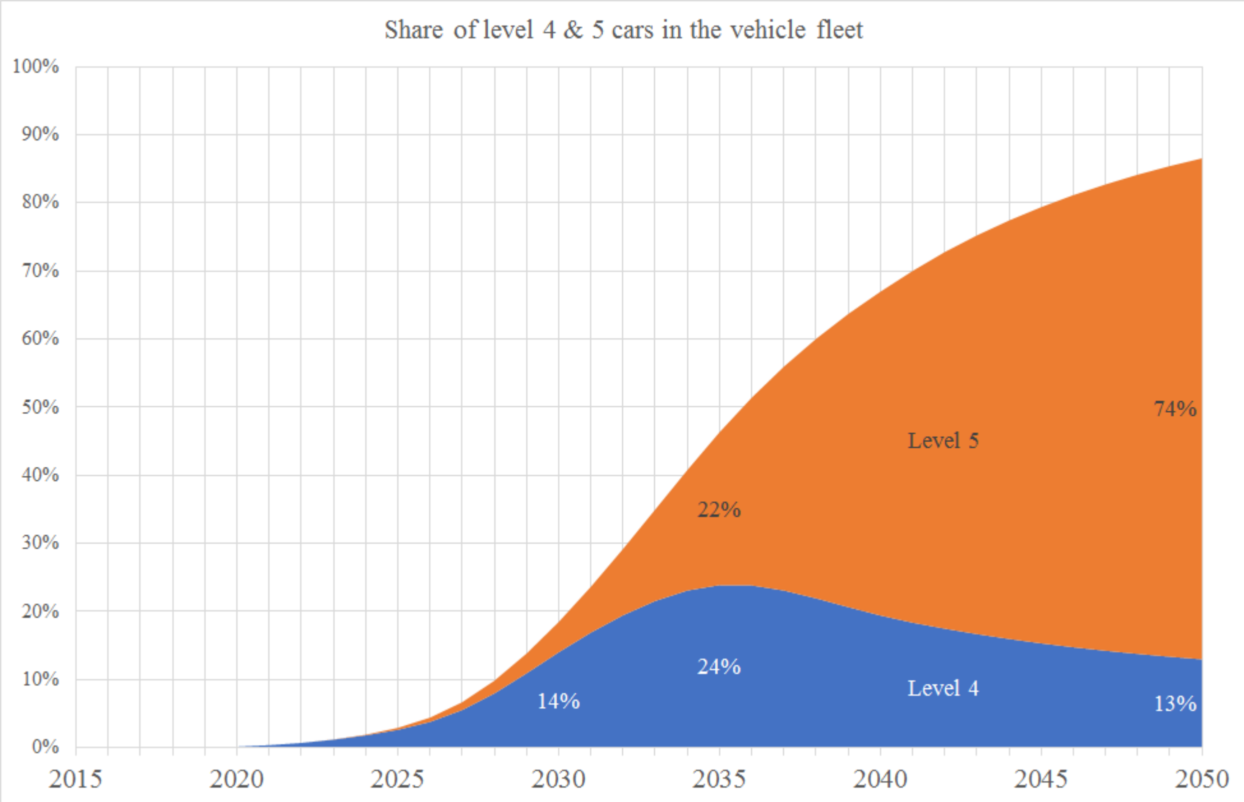

Fig. 2. Development of share of AV technologies.

5.1. Key indicators for Leeds in 2050

Table 3 shows the key indicators of travel for 2050 and table 4 shows the mode share and point changes for 2050 for all ten scenarios.

Table 3. Key indicators of travel for 2050 per scenario

	Car-km	Car speed Peak	Pkm-slow	Pkm-pt	Pkm-car	Pkm-total
Scenario 0	100.0	100	100.0	100.0	100.0	100.0
Scenario 1	113.4	140	107.3	112.6	116.1	114.8
Scenario 2	102.2	85	89.6	85.3	101.8	97.0
Scenario 3	113.2	95	106.3	105.5	115.3	112.4
Scenario 4	106.7	86	87.4	83.0	106.0	99.2
Scenario 5	156.2	107	87.2	81.5	163.4	138.6
Scenario 6	116.2	131	97.9	107.9	119.9	115.8
Scenario 7	103.1	73	74.9	73.7	102.0	93.4
Scenario 8	113.7	84	96.1	98.7	116.2	110.7
Scenario 9	141.4	113	90.3	95.8	148.4	132.0

Table 4. Mode share (trips) and point shifts for 2050

	car	PT	Slow	%change car	%change PT	%change slow
Scenario 0	53.0%	26.3%	20.7%			
Scenario 1	53.9%	26.2%	19.9%	1.0%	-0.2%	-0.8%
Scenario 2	58.9%	22.5%	18.5%	6.0%	-3.8%	-2.2%
Scenario 3	54.7%	25.2%	20.1%	1.7%	-1.1%	-0.6%
Scenario 4	58.3%	22.8%	18.9%	5.3%	-3.5%	-1.8%
Scenario 5	70.1%	16.0%	13.9%	17.1%	-10.3%	-6.8%
Scenario 6	58.7%	23.5%	17.7%	5.8%	-2.8%	-3.0%
Scenario 7	64.6%	19.4%	16.1%	11.6%	-7.0%	-4.7%
Scenario 8	59.4%	22.5%	18.1%	6.4%	-3.8%	-2.6%
Scenario 9	68.0%	17.8%	14.2%	15.0%	-8.5%	-6.5%

S1 solely increases capacity. This increases the person-km by all modes. The additional capacity results in less time in peak (commuting) as indicated also by the significant increase in average speed in the peak and so, due to the constant time budget, we see more travel off-peak, so all modes have an increase in kms travelled. There is a slight shift in shares to car. S2 reduces park search time and removes access/egress times for parking. This results in a large mode shift to cars. Overall more time is spent in the peak due to greater congestion (with a 15% reduction in speed in the peak) meaning less travel overall and so we see a significant reduction in travel by non-car modes in the off-peak. S3, with the value of in-vehicle time lowered, results in a shift to car use with a lower average speed. This results in increased time being spent in the peak but due to the lower unit value of time this still translates into a lower value of time spent in the peak and so we see more travel in the off-peak. Thus we see increases in person-km for all modes. S4 increases the availability of the car which results in a significant mode shift despite being subject to current car costs. This results in a significant reduction in average speed, and there are no time budget savings so we see a slight reduction in overall person-km. S5 combines all the changes from S1-4. This brings greater synergies than perhaps expected. We see more than a 56% increase in car-kms, though with a greater average speed, and a 38% increase in overall person-kms, while travel by slow modes and public transport fall by 13% and 18% respectively. This synergy is explained by the fact that the impacts in S1-3 are not extended by greater car availability. The combined effect of all benefits with the extended car availability results in significant increases in car use.

All the scenarios S6-S9 assume access to a car club which means there will be greater availability of AVs than in S5 or S4; however this greater availability is tempered by the charge per km reflecting the full costs of car use. S6 solely increases capacity. In comparison with S1 there is a greater increase in car use with a slightly lower increase in speed, and a small increase in person-kms reflecting reduced use of other modes. S7 with reduced parking search time and with access/egress times for parking removed results in a larger shift to car use than in S2 (with an even greater reduction in speed), hence without the increased capacity travel time in the peak increases which means there is less travel overall. S8 with a lower value of time again results in a greater shift to car use than in S3 despite the charge per km. However, changes in car-km, speeds and person-km are little changed from S3. S9 combines the changes from S6-8. Again there is evidence of synergy, but compared to S5 we see fewer car-kms despite greater availability as a result of the charge per km. These results are obviously dependent on the charge per km we have assumed and some sensitivity tests around this value would be in order.

5.2. Further comparisons of S0, S5 and S9

In this section we look at the changes over time for scenarios 0, 5 and 9 which represent the base, full automation with AVs privately used and full automation with AVs publicly shared. We do this so that we can infer something about the developments of the two main options over time. Figures 3-5 show the development of car-km, car person-km, PT person-km, slow person-km total person-km per resident and peak car speed as an index from 2015 base for these three scenarios respectively.

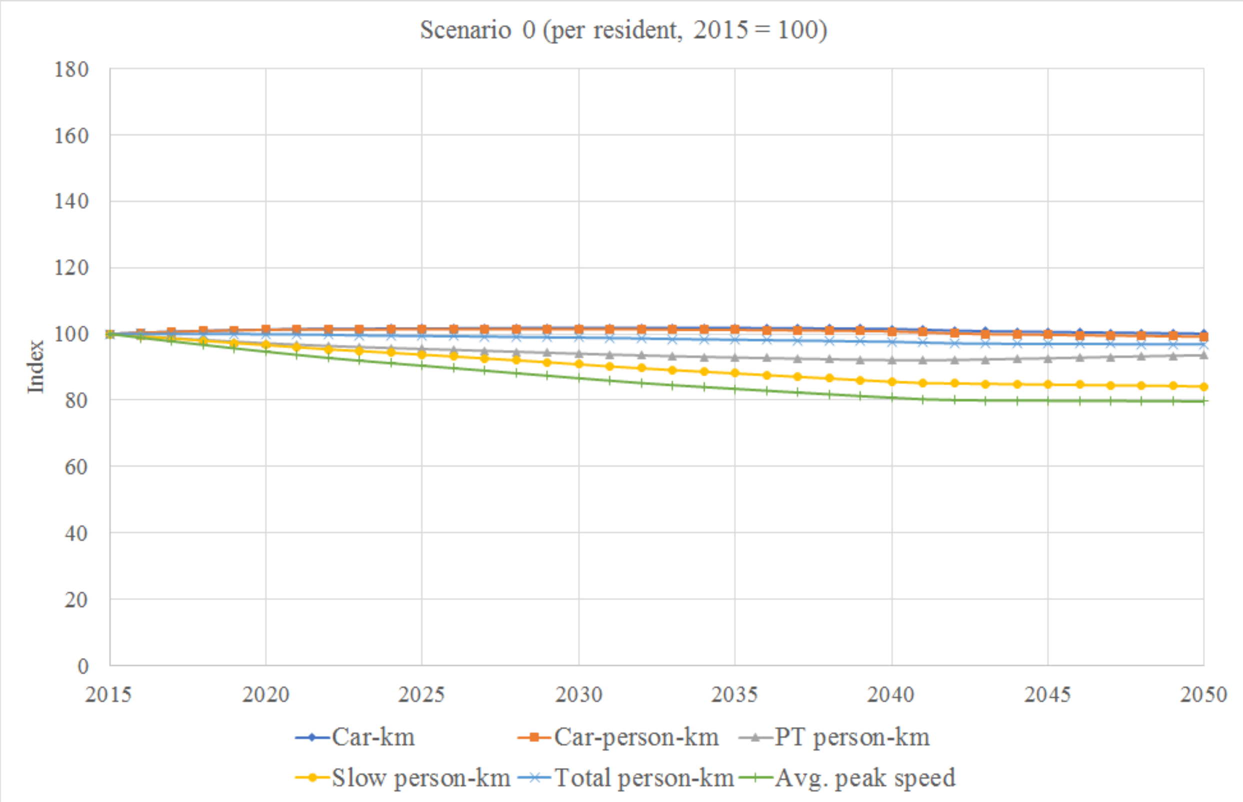

Fig. 3. Development of indicators per resident (2015 = 100) – Scenario 0

Figure 3 shows that in the base case there is a trend towards fewer person-km per resident over time with most of the reduction being in slow and PT-kms per person. There is a small increase in car-km mid period but by 2050 we see the same car-km per resident as in the base case. Due to population growth total car-km increase by about 20% leading to a decline in car speed peak of roughly the same order of magnitude. On a per person level this offsets the effect of car ownership growth resulting in a more or less stable value of car-km per resident.

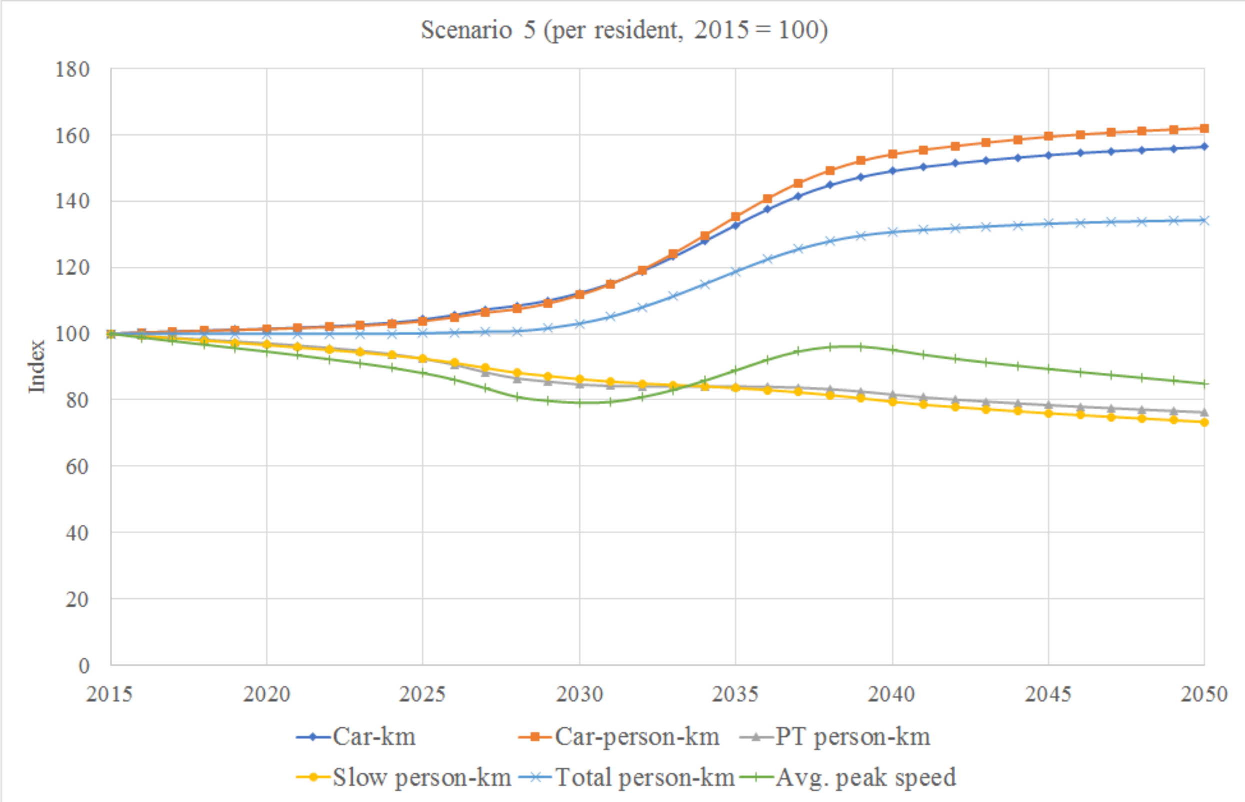

Fig. 4. Development of indicators per resident (2015 = 100) – Scenario 5

Figure 4 shows a significant increase in car-km and car-person-km per resident as the share of AVs increases bringing with it greater car availability. This increase in car travel per person is accompanied by a reduction of more than 20% in PT and slow person-kms per resident. The total person-km per resident is increased by 34%. While AVs increase individual attractiveness to use cars already at low shares, significant capacity gains do not come into effect until higher shares are reached. This leads to decrease of peak car speed relative to S0 up to about 2034. Between 2034 and 2039 capacity gains increase peak car speed again to nearly the same values as in the base year. In the last decade volume effects again cause slightly declining peak car speed.

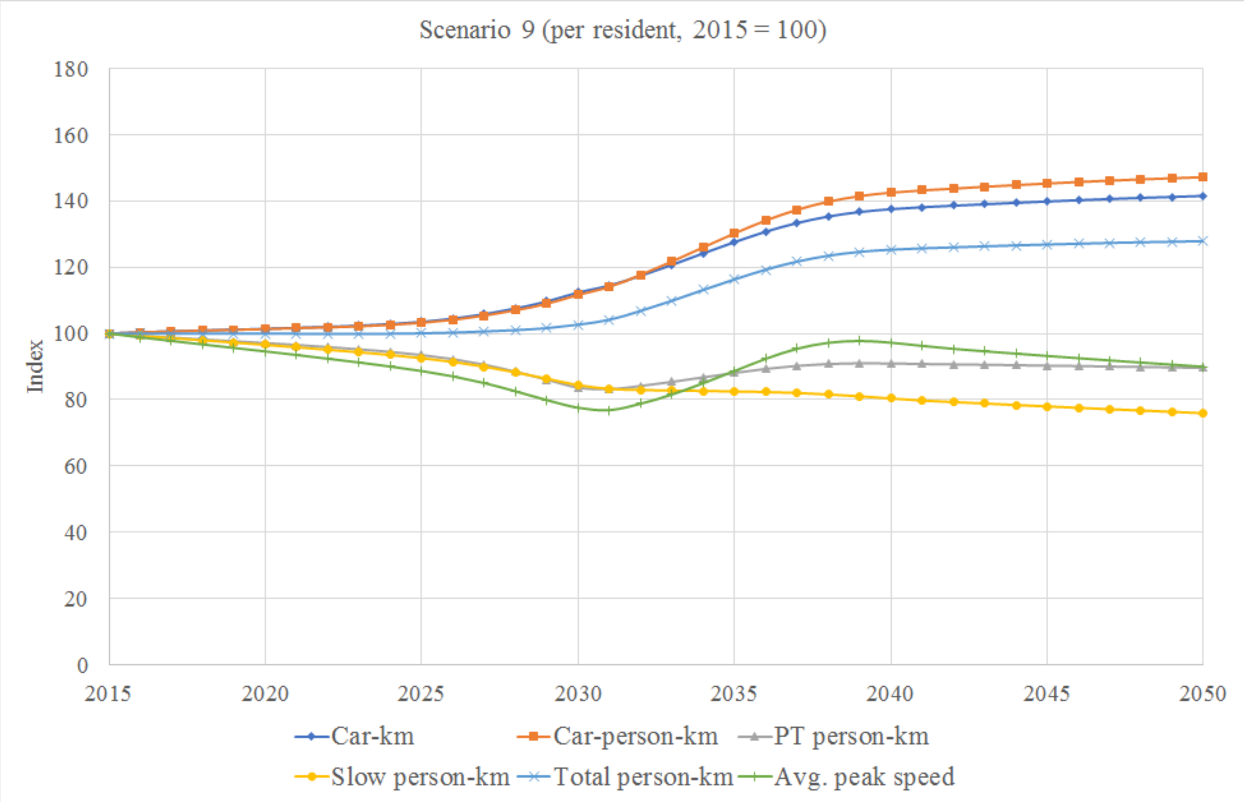

Fig. 5. Development of indicators per resident (2015 = 100) – Scenario 9

Figure 5 shows a similar pattern for scenario 9 but with lower increases in car travel and total travel per resident and slightly lower reductions in PT and slow person-kms per resident. The main difference here is that there is an increase in PT and slow person-kms just after 2030 as the share of AVs begins to increase, due to the charge per km being introduced for shared AVs. This results in a slightly lower increase in total person kms of around 28%. Peak car speed follows roughly the same pattern as in S5. While in the earlier years the decline is slightly delayed compared to S5, the recovery in the middle years is more and the decline in the later years is less pronounced than in S5.

From the above figures we can make some inferences about other impacts on the environment. If we assume emissions follow car-km per person for example then the introduction of either system would see an increase in car related emissions of around 56% and 42% per resident for S5 and S9 respectively. This would obviously be dependent on future propulsion technologies.

5.3. Impacts on urban sprawl

It was hoped that we would be able to identify changes in the distribution of population as a result of the trends above. However, the initial Leeds model results showed little or no change in many of the zones as by 2050 most zones had been fully developed and so were constrained in terms of relocation response by residents. We therefore investigated a low growth scenario where we re-ran S0, S5 and S9 with only a 0.2% instead of a 0.7% growth rate for the population until 2050. This allows us to see the hypothetical changes in land use associated with these schemes as some land is generally now still available in 2050. Figure 6 shows the change in share of Leeds residents by area (city centre, inner area and outer suburbs), for S5 and S9 relative to S0 in 2050. S5 causes an increase of 0.7% in the outer area (5,782 residents) with decreases in the city centre and inner areas of 0.6% (4,527) and 0.2% (1,255) respectively. This is direct evidence of the potential for urban sprawl and is associated with the greater availability of

AVs and lower generalised costs. In contrast S9 shows the opposite effect. S9 results in a 1.2% (9,194) increase in the city centre, 0.4% (3,529) increase in the inner area and a 1.6% (12723) reduction in the outer area. This is a move towards a more compact city and is due to the increase in costs per km associated with the shared AVs. So despite the increased car availability in S9 we see a more compact city. This result is to be taken in the context of the charge per km selected for this study and lower charges would perhaps result in similar patterns to S5.

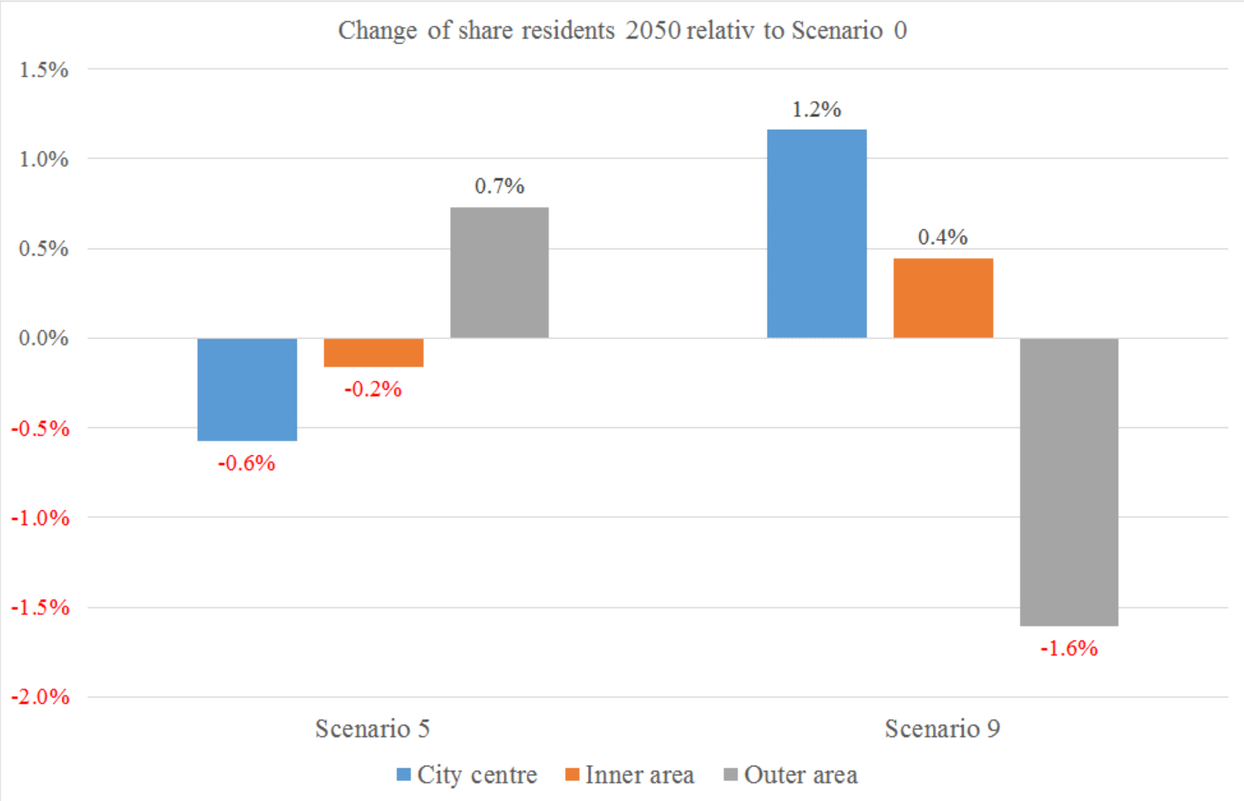

Fig. 6: Percentage change in population in 2050 by area relative to Scenario 0 for low population growth

6. Conclusions

Fully automated cars are likely to appear on public roads within the next decade. They are being promoted as ways of improving network capacity and reliability, making car use available to a wider range of people and reducing accidents. However, several researchers have suggested that they could lead to a significant increase in car use, with a parallel reduction in walking, cycling and public transport, and that this could more than offset the benefits of capacity increases and lead to urban sprawl. Our own review of the literature and qualitative analysis using causal link diagrams suggest that the most significant triggers of such changes will be the market share of automated vehicles, whether they are available privately or as shared vehicles, the extent to which capacity is increased, the potential for reducing time spent in parking and access, the possible reduction in the value of in-vehicle time and the expansion in the numbers of people able to drive.

In this paper we have used a systems dynamics model, MARS, for the city of Leeds UK, to test the impact of one set of assumptions for each of these triggers over the period from 2015 to 2050. The starting point for the analysis was to reprogram MARS to incorporate the main influences identified in the literature review and causal link diagram. We based our tests on the highest levels of market share in the literature, and used a stock flow model to predict the fleet share in each year, giving a fleet share in 2050 of approaching 90%.

The individual triggers all increase kilometres travelled by car compared with the business as usual scenario, with the largest effects arising from capacity improvement and reduced value of in-vehicle time. These two factors also increase total person-km travelled, while reduced parking costs and increased access to cars have the net effect of reducing person-km travelled slightly. As a result person-km by slow mode and public transport fall under these two triggers. Peak car speeds only rise in the case where capacity is increased; other factors lead to a reduction in speed compared with the business as usual scenario because of the offsetting effect of increased car use.

The combination of these triggers has a synergetic effect. In the case of privately owned automated cars, this principally involves the interaction with the expansion in the numbers able to use automated cars (S4). As a result in S5 kilometres travelled by car increase by 56% compared with the business as usual scenario; total person-km increase by 39%, person-km by public transport fall by 18% and person-km on slow modes by 13%. The net effect on peak car speed is to increase it by 7%.

However, in S9, which combines all the triggers with automated cars shared, synergy still occurs, even though all scenarios S6, 7 and 8 assume an expansion in the numbers able to use them. The effects found in S5 are tempered by the assumed charge for using these vehicles of €0.55/km, which broadly equates to today's car sharing charges. This results, in S9, in smaller changes from the business as usual scenario of a 41% increase in car-km, a 32% increase in person-km and reductions of 4% and 10% for public transport and slow modes. The net effect on peak car speed is to increase it by 13%. Preliminary sensitivity tests, not reported here, suggest that these results are very sensitive to the charge imposed; with no charge public transport use falls dramatically.

The increases in car-km suggest that, other things equal, the environment will be adversely affected. The decline in person-km by public transport suggests a loss in accessibility for those dependent on it; the decline for walking and cycling implies a loss in the health benefits which these modes afford; while the increase in person-km per capita suggests a tendency to urban sprawl. We were able to assess the impacts on population distribution with a modified version of the model, in which opportunities for development remained available through the period to 2050. This confirmed that with private ownership of automated vehicles there would be a tendency to urban sprawl. However, under shared ownership there was instead a tendency to densification as a result of the relatively high charge imposed per km travelled.

These results are dependent on our input assumptions, but they suggest that it will be important to gain a clearer understanding of the likely scale of each of the factors which we have considered: 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, accessibility, health, urban sprawl and overall sustainability. They also indicate that these adverse impacts can be tempered by the imposition of a requirement that automated vehicles in cities be made available as shared vehicles rather than privately owned ones. However it appears that, to be effective in avoiding these negative impacts, the charge will have to be higher than that currently imposed by car sharing companies.

There are a number of factors which we have not been able to model and which might further aggravate these effects, including the propensity for automated vehicles to travel empty to base or to collect the next shared user, and the response of public transport operators to declining patronage. Conversely, we have made no assumptions on the opportunities for automation of public transport, which could offset some of these effects. We plan to assess these factors, and also to extend our analysis to a second city, in further research.

Acknowledgements

We would like to thank the Austrian Federal Ministry for Transport, Innovation and Technology for funding the project “Systemszenarien Automatisiertes Fahren in der Personenmobilität” (System scenarios automated driving in passenger transport) in its program “Mobilität der Zukunft” (Mobility of the future). Elements of the qualitative analysis stem from this project.

References

Atkins W S (2016). Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow. Summary report. https://assets.publishing.service.gov.uk/impacts_of_connected_and_autonomous_vehicles.

BMVIT (2016). Automatisiert - Vernetzt - Mobil, Aktionsplan Automatisiertes Fahren, Bundesministerium für Verkehr, Innovation undTechnologie. Wien, https://www.bmvit.gv.at/service/publikationen/innovation/mobilitaet/downloads/automatisiert.pdf, Accessed: 07/06/2018.

Car2go (2018). How much is car2go? , https://www.car2go.com/AT/en/wien/costs/, Accessed: 04/07/2018.

DriveNow (2018). DriveNow prices at a glance, https://www.drive-now.com/at/en/pricing, Accessed: 04/07/2018.

Glotz-Richter M (2015). How a city government can support the car-sharing development - the eight treasures for the successful implementation of car-sharing. Freie Hansestadt Bremen.

Hensher D A (2018). Tackling road congestion - what might it look like in the future under a collaborative and connected mobility model? *Trans. Policy* **66** A1-8.

Her Majesty’s Government (2017). Industrial strategy – building a Britain fit for the future. https://www.gov.uk/government/policies/industrial-strategy.

International Transport Forum (2015). Urban mobility system upgrade: how shared self-driving cars could change city traffic. Corporate Partnership Board Report. Paris: OECD.

International Transport Forum (2016). Shared mobility: innovation for liveable cities. Corporate Partnership Board Report. Paris: OECD.

International Transport Forum (2017). Shared mobility simulations for Helsinki. Corporate Partnership Board Report. Paris: OECD.

Kyriakidis M, van de Weijer C, van Arem B and Happee R (2015). The deployment of advanced driver assistance systems. In: Europe Paper Presented at the ITS World Congress, Bordeaux.

MacKenzie et al. (2016). Will robot cars drive traffic congestion off a cliff? https://www.pbs.org/newshour/nation/will-robot-cars-drivetraffic-congestion-off-a-cliff.

McKinsey & Co. (2016). Automotive revolution – perspective towards 2030. https://doi.org/10.1365/s40112-016-1117-8.

Milakis D, Kroesen M and van Wee B (2018). Implications of automated vehicles for accessibility and location choices: evidence from an expert-based experiment. *Trans Geog* **68** 142-148.

Muir H. et al. (2008). Modelling background report - MARS, microsimulation, cities and scenarios. CityMobil Project Deliverable D2.3.1. http://www.citymobil-project.eu/downloadables/Deliverables/D2.3.1-PU-Modelling%20report-CityMobil.pdf.

Nieuwenhuijsen J, Correia G H, Milakis D, van Arem B and van Daalen E (2018). Towards a quantitative method to analyze the long-term innovation diffusion of automated vehicles technology using system dynamics. *Trans Res C* **86** pp 300-327.

Pfaffenbichler, P., Emberger, G. & Shepherd, S., 2008. The Integrated Dynamic Land Use and Transport Model MARS. *Networks and Spatial Economics*, **8** (2-3), pp 183-200.

Pfaffenbichler, P., Emberger, G. & Shepherd, S., 2010. A system dynamics approach to land use transport interaction modelling: the strategic model MARS and its application. *System Dynamics Review*, **26** (3), pp 262 - 282.

Pfaffenbichler, P., 2011. Modelling with Systems Dynamics as a Method to Bridge the Gap between Politics, Planning and Science? Lessons Learnt from the Development of the Land Use and Transport Model MARS. *Transport Reviews*, **31** (2), pp 267 - 289.

SAE, (2016). Taxonomy and definitions for terms related to on-road motor vehicle automated driving systems (Vol. SAE international’s J3016). https://www.sae.org/standards/content/j3016-201609.

Shladover S (1995). Review of the state of development of advanced vehicle control systems. *Veh. Syst. Dyn.: Int. J. Veh. Mech. Mob*. **24 (6–7)**, pp 551–595.

Shepherd S, Muir H. and Pfaffenbichler P (2008). Modelling automated technologies within a strategic transport model. Wien, REAL CORP 008.

Shepherd S and Muir H (2009). Strategic modelling results - summary of results across four cities. CityMobil Project Deliverable D2.3.2 http://www.citymobil-project.eu/downloadables/Deliverables/D2.3.2-PU-Results%20Model%20Tests%204%20cities-CityMobil.pdf.

Steer Davies Gleave (2017). CarPlus annual survey of car clubs: London 2016/17. London, CarPlus BikePlus.

Underwood S (2014). Automated vehicles forecast: vehicle symposium opinion survey. Proc: Automated Vehicles Symposium 2014, Burlingame, CA.

UITP (2017). Autonomous vehicles: a potential game changer for urban mobility. Policy Brief. Brussels: International Association of Public Transport (UITP). http://www.uitp.org/sites/default/files/cck-focus-papers-files/PolicyBrief_Autonomous_Vehicles_LQ_20160116.pdf.

Wadud Z, MacKenzie D and Leiby P (2016). Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Trans Res A* **86** pp 1-18.

Zakharenko R (2016). Self-driving cars will change cities. *Reg. Sci. Urban Econ*. **61**, pp 26–37.