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Automated vehicles and how they may affect urban form: A review of recent scenario studies

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ABSTRACT

Motorisation in cities has fundamentally transformed urban patterns of development, ranging from residential parking and density standards of single buildings on one hand to urban infrastructure construction and the expansion of entire cities on the other. The introduction of automated vehicles (AVs) has enormous potential to transform urbanisation patterns and urban design even further. However, the direction in which this technology will change the city is contested and a diverse set of views can be found. This paper provides a review of scenarios on these issues to date. Although some scenario studies provide useful insights about urban growth and change, very few consider detailed impacts of AVs on urban form, such as the density and mix of functions, the layout of urban development and the accessibility of locations, including the distance to transit.

1. Introduction

Within one or two decades, cities may witness the widespread introduction of fully automated vehicles (AVs), vehicles capable of sensing the urban environment and navigating without human input. These vehicles have the potential to fundamentally transform urbanisation patterns, urban spaces, street life and the quality of cities to a similar extent as the introduction of the first motorised vehicles in the city. Optimists point to the potential for AVs (especially when shared) to substantially reduce the total number of vehicles in the city, creating the opportunity for more car-free areas (e.g. parks, squares), whereas pessimists speak of the risk of more suburbanisation and urban sprawl as a result of longer travel times and distances that are considered acceptable due to the increased opportunities to work (or relax) while travelling by AV (see for example Papa & Ferreira, 2018).

Assessing the long-term impacts of AVs on urban development is difficult and complex since many impacts are dependent on decisions related to the future role of AVs in society and in the city (Litman, 2019; Townsend, 2014). These include decisions such as where and when AVs will be allowed to drive in the city, whether AVs can be operated alongside human driven vehicles (or segregated), how car users (of both conventional and automated vehicles) will respond to the introduction of AVs, whether AVs will be primarily used as private or shared vehicles, and the degree of safety and security they manage to achieve. To understand a range of possible impacts of AVs, several studies involving scenario-building exercises have been carried out in recent years. While many of them focus on the technical aspects of their introduction, relatively few studies consider the potential impact of AVs on spatial development of cities, which is the main focus of this review. Amongst the scenario studies exploring how AVs may impact cities in the long term, several aspects of impacts on urban form have been considered, including parking, road capacity and residential location.

Various researchers have started to consider the potential positive and negative effects of this technology on the city. Speculation about the potential future impacts of AVs on urban development has captured the attention of urban planners and designers around the world (Stone, Ashmore, Scheurer, Legacy, & Curtis, 2018). However, there is little consensus about the future impacts of AVs on urban development, sometimes not even in terms of the overall direction of change for certain types of impacts (Table 1). Conjecture still abounds when it comes to the potential impacts of AVs on urban development patterns and the quality and use of urban space (Cavoli, Phillips, Cohen, & Jones, 2017). According to Papa and Ferreira (2018), vehicle automation may open the door to a large variety of technological, design-related, legal and cultural changes that could either improve or worsen accessibility in urban environments. Whatever the direction of these changes in accessibility, the introduction of a new transport technology like AVs is likely to have significant impacts on urbanisation patterns.
and urban form. AVs will also have implications for the governance of urban development and urban transport (Stone et al., 2018). In parallel, urban planning policies and spatial development decisions will influence the design, introduction and take-up of AVs in the city.

It is important to recognise here that the introduction of a new technology like AVs can have multiple and often parallel impacts on the transport system (see for example Cohen-Blankstein & Rotem-Mindali, 2016). First, new technologies have the potential to change travel demand directly by reducing, inducing or modifying travel patterns. Second, new technologies have the potential to change the capacity of transport infrastructure and thereby affect the efficiency (and/or capacity) of the transport system and transport users’ behaviour. Third, new technologies can directly affect urban development patterns which in turn can influence urban mobility patterns.

AVs represent a potentially highly disruptive technology that could lead to shifts in mobility patterns and urban development of a similar order of magnitude as the first introduction of the car, metro or tram. Moreover, AVs have the potential to transform the urban form of the city which in turn can have a strong influence on travel patterns, transport demand and infrastructure use. At the same time, travel patterns, transport demand and infrastructure use can all influence urban form (Kasraian, Maat, Stead, & van Wee, 2016). Urban form is concerned with the physical characteristics of built-up areas, including the shape, size, density and configuration of development (RTPI, 2015). It can be considered at a range of different scales, varying from regional to local (see for example Stead & Marshall, 2001), and frequently measured in terms of five inter-related dimensions: density (of activities), diversity (of land uses), design (of streets and paths), destination accessibility (to jobs or services) and distance to transit (see Ewing and Cervero (2010)).

The aim of this paper is to review and synthesize the content of the different types of scenarios that have been put forward in recent studies concerning the introduction of AVs and their implications for urban form. While some of these studies consider the role of urban form in influencing the introduction and take-up of AVs, most consider the reverse relationship – the way in which the introduction and use of AVs may affect the future development of urban form.

The paper is divided into five main parts. The first part considers the role and importance of scenario studies for long-term decision-making in transport and urban planning. The second part outlines the research approach and methods employed to identify and review the various scenarios of AVs and their impacts on cities. In the third part, recent scenario studies are reviewed and a synthesis of their findings is presented, including an overview of the extent to which the scenario studies have considered different aspects of urban form. Fourth, the paper identifies gaps in attention to different aspects of urban form (i.e. the scales or types of urban form which the scenario studies do not consider). In the fifth and final part, the conclusions of the research are identified together with potential new directions for future research.

2 Ewing and Cervero (2010) refer to these dimensions as the five Ds.
situations of high uncertainty such as long timescales or rapid technological changes. Considering and comparing alternative scenarios, reflecting major uncertainties, can provide useful information for policy-makers (and academics) about how to anticipate and respond to future developments and can provide insights into ways of avoiding adverse outcomes that might occur in the future. In order to understand the nature of future transport systems, an important part of scenario-building is the identification of key factors which may determine qualitatively different paths for the socio-economic environment. May (1982) identifies a number of potential benefits of policy scenarios to decision-making, including:

- providing useful frameworks for decision-making – scenarios allow decision-making issues to be explored using a range of alternative scenarios, reflecting different assumptions about the future;
- identifying dangers and opportunities – considering a range of alternative futures increases the likelihood of identifying possible problems and opportunities in policy-making; suggesting a variety of possible approaches – the use of scenarios may generate a range of approaches to tackle issues or problems whereas the use of forecasts, often based on single theories or simple extrapolations, often leads to the pursuit of singular solutions;
- helping to assess alternative policies and actions – scenarios may for example be used to identify the usefulness of different policies under alternative future conditions; and
- increasing creativity and choice in decision-making – identifying possible future developments and avoiding the acceptance of current trends as inevitable opens up new possibilities for policy development.

While scenario studies offer a number of benefits, it is recognised that there are also limitations associated with their use. First, like any other form of considering long-term futures, scenario studies are always a simplification of reality since they cannot include all possible factors or developments that will occur. Second, scenario studies can never provide a completely accurate view or image of the future since there are often many unpredictable factors involved and an almost infinite number of alternatives and variables regarding what may and may not happen in the future. Third, a range of methods and techniques can be employed for constructing scenarios, which can result in a diverse set of interpretations about future development.

3. Research methods

This paper reviews the scenarios contained in recent studies drafted during the last 5 years (2013–2017), most of which employ exploratory approaches (see below). All of the studies reviewed in this paper consider the issue of urban form and structure to some degree (some go into more detail than others). Scenario studies that do not consider the impact on urban form and structure were not included in this review. The scenarios contained in these papers and reports present a range of different futures, the majority of which is speculative in nature (as opposed to predictive). The scenario studies reviewed in this paper come from a mixture of two main sources: (i) academic papers (journals, conference proceedings and books); and (ii) reports produced by government agencies or consultants. The studies were identified using a keyword search in Scopus and Google Scholar (using combinations of the keywords: self-driving, automated, autonomous, vehicles, land use, space, spatial, scenarios) supplemented by forward and backward snowball techniques. Each of the scenarios reviewed in this paper have been classified into one of four main types. These types were inductively developed on the basis of the main content and assumptions of the scenarios. This classification distinguishes between the following four main types:

1. Business as Usual (BAU). Reference scenarios which assume the continuation of one or more current trends (in mobility, urban development and/or demographics), without the introduction of AVs.
2. Technology + Non-Shared (T). Scenarios which assume the introduction of AVs which are either solely or predominantly individually owned and used.
3. Technology + Shared (T+). Scenarios which assume the introduction of AVs which are solely or predominantly shared.
4. Technology + Shared + Infrastructure/Policy (T++). Scenarios which assume the introduction of AVs which are solely or predominantly shared. In addition, supportive policies and/or infrastructures are introduced to actively promote the uptake and use of AVs.

In total, 13 literature sources were identified and selected for review in this paper, comprising three academic reports (Fulton, Mason, & Meroux, 2017; Pernestål Brenden, Kristoffersson, & Mattsson, 2017; Townsend, 2014), three government agency reports (Chapin et al., 2016; International Transport Forum, 2015; Tillema et al., 2015), two conference papers (Gruel & Stanford, 2016; Thakur, Kinghorn, & Grace, 2016), two consultants’ reports (Bouton, Knupfer, Mihov, & Swartz, 2015; Corwin, Vitale, Eamonn, & Cathles, 2015), one journal article (Milakis, Snelder, van Arem, van Wee, & Correia, 2017), one book chapter (Heinrichs, 2016) and one report from a transport umbrella organisation (Röhrleef, Deutsch, & Ackermann, 2015). Almost all the sources contain several scenarios (Table 2), each of which are reviewed below. As can be seen in Table 2, the majority of studies uses scenarios for exploratory purposes while most of the other studies use scenarios in order to develop forecasts.

4. Content of scenarios – assumptions about future travel and land use patterns

4.1. Business as usual (BAU)

Of the 13 papers reviewed, 6 papers contained a Business as Usual scenario. Of the ones which specify a time frame, they range from 2028 to 2050. While several papers are global in scope (e.g. Corwin et al., 2015; Fulton et al., 2017), others focus on specific countries such as Australia (Thakur et al., 2016), Germany (Heinrichs, 2016; Röhrleef et al., 2015), Netherlands (Milakis et al., 2017; Tillema et al., 2015) and the United States (Townsend, 2014).

The Business as Usual scenarios largely assume that current trends, attitudes and priorities remain largely unchanged in the future. These trends refer amongst other things to changes in technology, economics, demographics and politics. The underlying assumptions here are that technological innovations are not taken up to any great extent, particularly due to the high cost of the necessary infrastructure. Significant technological development does take place and is mainly restricted to efficiency gains in specific areas (Heinrichs, 2016). The scenarios

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3 In fact, the main purpose of many scenario studies is not to predict the most plausible or likely future but to illustrate the range in different possible futures.

4 Many other scenario studies can be found which examine various impacts of AVs (e.g. VMT, modal share, energy consumption) but do not consider how AVs may affect urban form (e.g. Childress, Nichols, Charlton, & Coe, 2015; Meyer, Becker, Bosch, & Axhausen, 2017; Trommer et al., 2016).

5 The forward snowball method involves searching for newer articles which cite any of the studies already on the list of papers to be reviewed. The backward snowball method involves searching for older articles cited by studies on the list of papers to be reviewed.

6 A few scenarios which do not closely fit into the classification presented above are not included in the review.

7 Time frames in some studies are not explicitly stated.
generally assume that car ownership and travel gradually rise (Fulton et al., 2017).

While most of the assumptions are made on the basis of current polices and trends in the cities, others consider the importance of factors such as ownership of vehicles, travel time and new mobility models such as ridesharing for evaluation of the impact of automated technology. Of the few scenarios which do mention urban form or land use, the BAU scenario in Heinrichs (2016) assumes that cities still continue to be dominated by cars and are characterised by low-density, fragmented settlement structures.

4.2. Technology + non-shared (T)

The technology and non-shared scenarios assume the introduction of AVs which are either solely or predominantly individually owned and used. Of the literature reviewed, ten of them contain scenarios very similar to this concept (Table 1). Various scenarios assume a gradual roll-out of automated vehicles and relatively widespread adoption of AVs from around 2020, and a rapid growth in AVs around 2025. These scenarios generally assume a continuation of existing trends for vehicle sharing, public transport use, and urban planning (e.g. Bouton et al., 2015; Fulton et al., 2017; Röhrleef et al., 2015). Meanwhile, vehicle ownership does not change significantly as individuals are attached to the ownership of their own cars (Corwin et al., 2015; Gruel & Stanford, 2016; Thakur et al., 2016).

In terms of impacts on land use, these scenarios assume that the demand for transport infrastructure and parking space may require large amounts of additional space in the city. In particular, this would lead to significant increases in the demand for parking in core areas of the city. Due to the low rates of sharing, traffic pressure in the city will increase. This will then result in the formation of urban sub-centres and/or the suburbanisation of some recreational and commercial functions (Tillema et al., 2015).

4.3. Technology + shared (T+)

The technology and shared scenarios assume a future state where automated vehicles are fully developed and the current mobility trends have changed and evolved along with the technology. Various mobility models such as ride sharing platforms, mobility on demand systems and car sharing platforms are expected to operate in cities. Almost all the literature reviewed contains one or more scenarios of this type (Table 2).

In these scenarios, shared vehicle services expand rapidly in terms of geographical coverage and customer segments. Car-sharing is the norm. New forms of shared vehicles and ride-sharing platforms are often included in these scenarios. Many of these scenarios assume that ridesharing is generally seen as a more economical and convenient form of mobility, particularly for short point-to-point movements. As shared mobility serves a greater proportion of local transportation needs,
households begin to reduce the number of cars they own while others abandon ownership altogether.

Many of the scenarios assume a multimodal public transport system alongside highly networked (automated) mass taxi systems as the backbone of urban mobility with the formation of multimodal hubs. However, it is also conceivable that AVs (particularly when shared) may reduce the demand for conventional public transport. Due to the shared ownership of vehicles, a considerable reduction in the land consumption for urban parking spaces may be possible, providing opportunities for additional development in cities or more open space (see below). At the same time, a growth in low-density suburban development is envisaged in some scenarios.

4.4. Technology + shared + infrastructure/policy (T++)

Technology, Shared and Infrastructure/Policy scenarios (which assume the introduction of AVs which are solely or predominantly shared in conjunction with supportive policies and/or infrastructures to actively promote the uptake and use of AVs) are contained in only two of the literature sources reviewed (i.e. Fulton et al., 2017; Milakis et al., 2017). In these scenarios, shared automated mobility is combined with substantial policy support for electrification, automation, shared-use mobility and urban planning to promote walking, cycling and public transport use.

According to Fulton et al. (2017), strong policy support for compact
cities is needed to avoid significantly higher vehicle kilometres, even in a situation of fairly high levels of vehicle sharing in smaller vehicles. This scenario assumes that government coordination of mobility-as-a-service, linking many transportation options into a seamless network of trip planning and payment via a single interface and increased use of local development impact fees (e.g. charges that account for the negative externalities of car use in order to help fund investment in sustainable transport solutions). Other planning policies contributing to the implementation of shared AVs in cities include coordination of regional land-use and transportation decisions, increased, ongoing investments in walking, cycling, and public transport infrastructure and systems, implementation of bike and e-bike sharing programs in urban areas with sufficient density. Meanwhile, one of the scenarios put forward by Milakis et al. (2017) supposes that the growth in travel and urban expansion can be curbed when AV technology is combined with road pricing and stricter land use policies (e.g. compact city regulations).

5. Content of scenarios – potential impacts on urban form

The potential impacts of AVs on urban form are discussed below in terms of three interrelated issues, each of which encompasses one or more of the 5 Ds proposed by Ewing and Cervero (2010): (i) freeing up parking space/reallocating roadspace; (ii) improving the attractiveness
of the urban environment; and (iii) making more efficient use of transport infrastructure. In the majority of cases, issues of urban form are mainly discussed in the assumptions used to construct scenarios rather than being outputs or results from the scenarios (Table 3). Nevertheless, there are few studies in which the latter is the case (e.g. Chapin et al., 2016; Gruel & Stanford, 2016; Thakur et al., 2016).

5.1. Freeing up parking space/reallocating roadspace

The scenarios reviewed in this paper often consider that AVs will have a large impact on parking spaces, depending on the number and type of vehicles required. This is related to the type of scenario, particularly in terms of whether vehicles continue to be individually owned and used (as they are in the BAU and T scenarios) or whether they will be shared (as they are in the T+ and T++ scenarios). As such, AVs can have a significant impact on urban spaces and their quality. If individual car ownership decreases and vehicles are shared, more opportunities may arise for reallocating existing parking spaces. Some spaces could be converted into other uses, while others could be used more efficiently to accommodate vehicles in smaller spaces (e.g. stacked silos) since cars without drivers can be parked more closely together. New parking spaces can therefore be smaller. Moreover, AVs offer the potential to decouple car parking from other land uses since AVs can potentially take themselves away to another part of the city where parking is cheap (or free). As such, the location of parking does not have to be in close proximity to major transport destinations. The relocation of parking space from city centres to the outskirts is possible, thereby freeing up space in the city.

In situations where automated shared and on-demand vehicles are introduced, some of these may be in near continuous operation and have less need to park and may return to depots in less expensive locations where more land is available (e.g. on the urban periphery or industrial areas). This means that the amount of off-street parking could be significantly reduced in city centres. However, a substantial amount of space will still be needed for picking up and dropping off passengers, especially at transport interchanges and major destinations in the city (offices, public buildings, etc.). Clearly, these developments may substantially affect parking revenue for local governments which can represent a critical and substantial funding source for some local authorities (Gühnemann, 2009).

5.2. Improving the attractiveness of the urban environment

Lowering the amount of on-street parking offers more opportunities for reallocating urban space for use by transport modes that are cleaner and/or visually less intrusive (e.g. cycling, walking and mass transit). Freed-up parking space also has the potential to be used for public spaces (e.g. parks, gardens, café seating) to promote more attractive and/or visually less intrusive (e.g. cycling, walking and mass transit). Freed-up parking space also has the potential to be used for public spaces (e.g. parks, gardens, café seating) to promote more attractive

5.3. Making more efficient use of transport infrastructure

AVs provide opportunities to reduce the dimensions of carriageways (and parking spaces – see above) since they are potentially able to operate safely with shorter distances between vehicles, meaning that they can drive alongside each other or behind each other with lower clearances. Moreover, full introduction of AVs also offers the potential for removing some of the existing transport-related hardware from cities including traffic signals, direction and access signs and safety barriers. This can have benefits both for the costs of transport infrastructure as well as for the quality of urban streetscapes.

In addition, AVs provide new opportunities for more flexible use of road infrastructure, so that it can be used for different purposes at different times of the day (or week). Examples include pedestrian-only zones or public transport lanes at specific times of the day. Moreover, AVs can also reduce the need for features such as central reservations between carriageways on main roads, resulting in the potential for using the infrastructure more flexibly such as regulating the direction of flow of different lanes according to prevailing traffic conditions. Clearly, using transport infrastructure more efficiently can potentially generate additional traffic, particularly if travel times are reduced and/or reliability of transport times are increased. Consequently, attempts should not be made to reduce overall travel times for AVs if there is a desire to prevent suburbanisation.

5.4. Gaps in the literature

The review of the scenarios helps to identify various gaps concerning the potential impacts of AVs on urban form which is currently an under-examined issue in scenario studies of AVs. The effects on urban form can differ greatly depending on the type of AVs introduced, the extent to which they are shared system and the introduction of supporting policies and infrastructure. The impacts of different types of AVs (from individual pods to driverless trains) on future urban form are scarcely addressed in the scenarios. Most scenarios assume that AVs systems will have some significant impacts on the land-use patterns of cities. Some speculate more dispersed low-density land-use patterns surrounding metropolitan regions where AVs result in the further growth of suburbs and even push development and population into exurban areas (see also Soterospolus, Berger, & Ciari, 2019). On the other hand, others speculate that AV
technology reduces the need for parking space, thereby freeing up space for other uses (see for example Zhang and Guhathakurta, in press). Some estimates suggest that AVs could halve the demand for parking and reduce the demand substantially more if most AVs are shared (Dupuis et al., 2015; Milakis et al., 2017). However, it is still unclear how much urban parking space can be freed for other land uses since significant amounts of space will still be needed for passenger drop-off and collection. Moreover, there are many uncertainties about the spatial and temporal distribution of parking demand after AVs are introduced and used. Amongst other things, new spatial and temporal patterns in parking demand will be dependent on the degree of access in cities afforded to AVs, and the locations where they are permitted to collect and drop off passengers. Furthermore, there has been little attention to the inevitable peaks in transport demand and how these will affect the need for roadspace, collection and drop-off points and parking space.

Clearly, the price, location and availability of parking spaces across different parts of the city will affect the extent to which AVs circulate when not used (i.e. running empty) or reposition themselves in anticipation of passenger demand later in the day (Papa & Ferreira, 2018). The reallocation of roadspace and parking areas will affect the intensity of land uses. In general, many of the studies tend to devote more attention to exploring the small-scale impacts of AVs on urban form, such as parking spaces and carriageway dimensions, than the larger scale impacts such as suburbanisation and the reallocation of parking spaces to other parts of the city which lead to long term implications.

6. Conclusions and recommendations

Many scenarios suggest that fully automated vehicles might be introduced into the city within one or two decades. This will have significant implications for transport and urban planning policies. According to the different scenario studies reviewed, views about the potential consequences of AVs for urban development patterns are diverse. Some are much more optimistic about the impacts for city centres than others. Others suggest a picture of greater suburbanisation of cities (e.g. Gruel & Stanford, 2016; Heinrichs, 2016).

One possible long-term impact of the adoption of AVs is the development denser urban cores, more buildings and fewer parking spaces. At the same time, AVs could lead to a greater dispersion of low-density development in metropolitan fringe areas given the ability of owners to engage in other activities while vehicles drive themselves. These impacts may vary depending on how car-dependent a city is (e.g. Bouton et al., 2015). City governments need to have a clear appreciation of where urban land may become available as a result of any reductions in parking or infrastructure space after the adoption of AVs. A clear vision for the re-allocation or re-use of this space is needed.

Connections in decision-making processes between long-term mobility (location choice) and daily mobility (destination and transport mode selection) should be brought into debates surrounding the introduction of AVs. The extent to which suburbanisation may materialize as AVs are introduced, and how the impacts can be assessed, should be considered as a matter of priority.

The reduction of traffic management measures, combined with improvements in safety, lower emissions and less noise pollution have the potential to improve public realm, making it more attractive and more utilized. The space currently occupied by car parking or made unattractive by transport infrastructure could be put to new and innovative uses. To a limited degree, this has already begun in cities by introducing the concept of ‘pavements to parks’, which has started to encourage the conversion of roadside parking spaces (sometimes on a temporary basis) into new uses such as gardens and cafes (see also Pernestål Brenden et al., 2017; Townsend, 2014).

The role and position of mass public transport (e.g. trains, trams and metros) is crucial in shaping future urban form in cities as well as the roll-out of AVs. In some scenarios reviewed, AVs act in competition with mass public transport, such as shared AVs which operate with comparable tariffs and similar speeds as public transport. In other scenarios, mass public transport provides an essential transport backbone for the city while AVs primarily provide services that link to and from the mass public transport network. In order to achieve the latter, policies will be required to ensure that AVs work in concert with public transport and other highly efficient modes, rather than compete with them (see also Fulton et al., 2017). Policy options to achieve this might involve restrictions on operations within certain corridors and incentives to serve stations. Ultimately, the future role of AVs in influencing urban form and structure is not so much dependent on the technology and level of automation of vehicles but rather on the regulation of this technology and the governance of cities and regions.

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