How beneficial is fully automated driving in urban areas from a socio-economic point of view?

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ABSTRACT

Reviewing literature and results of model applications, the paper reveals that autonomous driving in urban areas can indeed raise considerable socio-economic benefits by reducing travel times, alleviating congestion, enhancing access to and comfort of individual motorized mobility, improving safety and facilitating various opportunities through the conversion of urban areas. However, in how far these benefits will occur, depends on manifold determinants, particularly critically on the high number of variables affecting vehicle mileage. A majority of the authors expect a net increase in vehicle mileage, since demand inducing factors (e.g., empty return transports, shift from competing modes, parking outside of city centers, additional demand by new user groups) are expected to outweigh demand reducing factors (e.g., relatively high variable costs of shared systems, decrease in ownership of privately owned cars, less traffic for searching parking places). The expected increase in vehicle mileage however, raises some uncertainty whether the potential of autonomous driving to generate socio-economic benefits will actually be exploited.

Keywords: autonomous driving, automated vehicles, socio-economic impacts, urban transport, passenger transport, model simulations, urban transport policy

1. INTRODUCTION

Automated driving is an emerging technology which is expected to penetrate substantially the global passenger car market: the Victoria Policy Institute (2015) expects the share of automated vehicles purchased in the period of time 2040–2050 to amount to 80% in the pessimistic and to 100% in the optimistic scenario, while the share of vehicle mileage by automated vehicles is predicted to range between 50 and 80 percent (Litman 2015). Navigant Research (2013) expects 75% of all new vehicle purchases worldwide to be automated vehicles in the year 2035, and McKinsey & Company (2015) forecast automated vehicles to become the preferred mode of transport before 2050 (Bertoncello and Wee 2015). In a recent publication, Information Handling Services (2016) increased their forecast for purchase of automated vehicles in the year 2035 by almost 100% compared to an earlier study conducted in 2014 (IHS 2014). This indicates that recent technical advancements have supported the assumption of an even wider diffusion of automated vehicles in the medium and long-term future than previously expected.

Transferring driving functions from a human driver to computers, a wide use of automated vehicles is considered to revolutionize mobility. Particularly the application of automated vehicles according to the Full Save-Driving Level 4, in which the driver "is not expected to be available for control at any time during the trip" (U.S. Department of Transportation 2013), or according to the "Full Automation" Level 5 defined by the Society of Automotive Engineers (SAE), will facilitate the emergence of new mobility patterns. In the context of the current paper we focus on the impacts of the use of fully automated vehicles, which in this paper are also referred to as "autonomous vehicles" (AV).

New mobility patterns will result in manifold transport sector-related and socio-economic effects. The impacts of fully automated driving are particularly high at the urban scale: Not only represents urban transport a significant share of the total passenger transport demand – about 25% for the countries of the European Union (European Commission 2013) –, it also generates severe impacts because of high population densities, and it has close relations with city planning aspects and land use patterns.

Therefore, this paper provides an overview of research findings on socio-economic impacts of autonomous driving in urban areas, by analyzing research findings of general research and studies, and findings of case studies where specific models have been developed and applied to selected cities.

The socio-economic benefits regarded in this paper are mainly those which are considered by a "standard CBA approach" (Veryard 2017), such as time savings, savings of operating costs, safety benefits, environmental benefits, and benefits by increase in comfort. Since many of these socio-economic impacts are largely driven by changes in the transport sector (e.g., impacts on travel time, network capacity, vehicle mileage), effects on the transport sector are considered in this paper, too. Also possible impacts on land use pattern are considered, whereas (macro-) economic impacts, such as effects on employment, economic output or profits, are beyond the scope of this paper.

This paper is organized as follows: chapter 2 provides a brief overview of the methodology underlying the paper. Chapter 3 provides an overview of socio-economic impacts of autonomous driving. In chapter 4 the case studies and their outcomes are presented. Chapter 5 embraces the synthesis of the reviews and recommendations for policy and research.

2. METHODOLOGY AND DATA COLLECTION

In order to provide an overview of socio-economic impacts to be expected from automated driving in urban areas, the paper provides a literature synthesis. The scope of this literature synthesis embraces (1) general research and studies on various socio-economic impacts of autonomous driving in urban areas and (2) specific case studies.

The first part tackling general research and studies on socio-economic impacts of autonomous driving in urban areas, includes work by Johanning and Mildner (2014), Hars (2010, 2014a), Eugensson et al. (2013), Rodoulis (2014), Litman (2015), Fagnant and Kockelman (2013), Ticoll (2015), Kückelhaus (2014), or Bradburn et al. (2015).

Enriched with outcomes of further research, a wide spectrum of expected impacts of autonomous driving in urban areas is elaborated.
The second part addresses case studies which refer to specific cities. In these case studies, the impacts of autonomous driving are assessed under application of specific models. The case studies embrace the following cities worldwide: Brisbane (Davidson 2011; Davidson and Spinoulas 2015); Lisbon (ITF 2015); Austin (Fagnant and Kockelman 2014; Fagnant, Kockelman and Bansal 2015); Ann Arbor (Burns, Jordan and Scarborough 2013); New York and Singapore (Pavone 2015) and Berlin (Bischoff and Maciejewski 2016). Each case study reveals different assumptions and modelling approaches. Since the main focus in this paper is attached to present results of the model applications, the modelling methodologies are only briefly described.

3. SOCIO-ECONOMIC IMPACTS OF AUTONOMOUS DRIVING

3.1 Transport Aspects

3.1.1 Vehicle Mileage

The impacts of autonomous vehicles on vehicle-miles travelled (VMT) reveal ambiguous patterns: there are both effects which support an increase in vehicle mileage, and effects which suggest a decline.
Because of higher safety levels for vulnerable road users and less demand for urban parking spaces – resulting in conversion of parking spaces for other purposes –, the attractiveness of living in urban areas is expected to improve. If citizens decide to live in urban areas instead of suburbs, commuting trips will become shorter, resulting in an overall decrease in vehicle mileage (Litman 2015). Furthermore, AVs will reach their destinations on optimal routes, without the possibility of losing their way (Claudel and Ratti 2015), and fully automated parking will reduce the volume of traffic searching for parking spaces which makes up 30% of urban traffic flows (Litman 2015). Moreover, AVs favor the usage of car sharing systems (Bierstedt et al. 2014), resulting in lower motorization levels and smaller car fleets. From the viewpoint of households, car sharing systems allow for reducing the fixed costs for individual mobility, since the purchase of a car is not required. On the other side, the variable costs of a shared car are significantly higher than the variable costs of a private car. Thus, also the perception of relatively high variable costs for mobility may lead to a decrease in vehicle mileage (see Anderson et al. 2014; Bradburn et al. 2015).
Regarding impacts on mode split between autonomous cars and public transport systems, two scenarios are imaginable: either autonomous vehicle fleets will become an integral part of the public transport system – resulting in a more efficient usage of public transport systems and a decrease in vehicle mileage by cars – (Litman 2015), or public transport trips are shifted to passenger cars resulting in an increase in car vehicle mileage (Barcham 2014; VDV 2015).
Other effects tend to increase the vehicle mileage. Sivak and Schoettle (2015) estimate additional demand by 11%, since autonomous cars facilitate access to individual mobility services for citizens without driver license, and for elderly and mobility-impaired citizens (see section 3.3.3). Harper et al. (2016) have estimated a demand potential of 14% by fully automated cars in the US by non-driving, elderly and people with travel-restrictive medical conditions. Furthermore, AVs provide benefits such as enhanced safety, avoidance of congestions by optimal route choice, and the possibility to conduct further activities during driving (e.g., Litman 2015). The overall reduction in

travel disutility is likely to result in increased demand. If lower travel disutility and improved accessibility by AVs cause citizens to move from city centers to residences in suburbs or the surrounding area of cities, a considerable increase in vehicle mileage can be expected (Anderson et al. 2014). Also return trips without passengers by shared autonomous fleet systems will result in an increase in vehicle mileage (Litman 2015). Privately used vehicles induce additional vehicle mileage for the ride between passenger drop-off and parking space (Anderson et al. 2014). Finally, it is presumed that autonomous vehicles will be used for purposes other than intended, such as for transporting objects (e.g., left smartphones), using vehicles as moving promotional platforms or even as playground for children and young people (Scientific Advisory Board of the German Ministry of Transport and Digital Infrastructure 2017).

Depending on a high number of different determinants, the net impact of autonomous driving on vehicle mileage is not unambiguous. However, the majority of the reviewed sources expect an increase in vehicle mileage. Fagnant and Kockelman (2013) predict an increase in VMT by up to 9%, if 90% of all vehicles are driven automatically. FP Thinks (2014) forecasts an increase by 35% for a market penetration of 75% in car-dependent regions and an increase by 25% in multimodal regions (Bierstedt et al. 2014).

3.1.2 Capacity

Road infrastructure capacity in urban areas is largely determined by the capacity of road links and junctions. The net impact of autonomous vehicles in terms of capacity is dependent on deceleration, acceleration, distance between vehicles, speed, the share of AVs and reaction times (see Bierstedt et al. 2014). Regarding decelerating and accelerating, AVs are faster, more precisely and thus more efficient than human drivers (Barcham 2014; Eugensson et al. 2013). This allows a more efficient use of green phases (Fagnant and Kockelman 2013), while the same acceleration of all vehicles prevents the concertina effect to happen and, thus, improves capacity (Hars 2014a). Because of their more concise steering mechanism and shorter reaction times, AVs can operate with lower distance to other (automated) vehicles, with regard to direction of travel and lateral space (Eugensson et al. 2013; Hars 2014a). The latter aspect sets the stage for introducing smaller lanes (Hars 2014a). On congested road sections and in front of junctions AVs are capable of reducing the number of driving disruptions by facilitating anticipative steering and coordinated traffic operations (see Anderson et al. 2014; Litman 2015) that result in higher speeds of autonomous vehicle fleets (Anderson et al. 2014). A traffic management system that is real-time connected to all fully automated vehicles, can be applied to determine routes optimal for the urban transport system, and to conduct maneuvers among autonomous vehicles such as changing lanes, turns and overtaking (Bradburn et al. 2015; Hars 2014a; Maerivoet 2015; Rodoulis 2014).

Furthermore, with an autonomous fleet the direction of road lanes can be defined in a more flexible way, allowing a demand-driven, dynamic allocation of lanes to directions. Allocating more capacity dynamically to the direction of travel with peak demand allows for alleviating traffic bottlenecks (see also WSP/ Parsons Brinckerhoff and Farrells 2016).

Finally, autonomous parking can enhance the capacity situation on urban road network, since traffic searching for parking spaces becomes obsolete. The decrease in traffic searching for parking spaces is expected to outweigh the traffic generated between drop-off location and the parking sight. The parking process of an auto pilot outclasses a capability of human drivers in terms of level of preciseness and time requirements (see e.g., Kückelhaus 2014), reducing traffic jams behind the parking vehicle.

3.1.3 Road Congestion

Delays caused by congestion can be distinguished by recurring disruptions and one-time disruptions. Traffic congestion caused by road accidents represents a significant share of the one-time disruptions. Thus the improvement of safety conditions by AVs results in a reduction of traffic disruptions caused by accidents.

The expectations regarding net effect on congestion are however ambiguous. According to Litman (2015) and Anderson et al. (2014) the net effects on road congestion are uncertain, since they depend on a high number of interdependent impacts. According to Fagnant and Kockelman (2013), the impact on vehicle mileage and demand management strategies, as well as the level of benefits such as capacity increase and avoidance of accidents, will determine whether congestion will de- or increase. Eugensson et al. (2013) as well as KPMG and Center for Automotive Research (CAR) (2012) expect a reduction of urban congestion by AVs.

3.2 Environment and Safety

3.2.1 Environment

The environmental impacts of autonomous driving depend on its effects on demand, particularly vehicle mileage. Furthermore, it depends on driving dynamics, vehicle characteristics and propulsion technology.

Several aspects of driving dynamics of autonomous vehicle fleet systems are expected to result in lower fuel (energy) consumptions: first, facilitating an anticipatory driving style, which reduces the number of acceleration and deceleration processes, results in a decrease of energy consumption. Fagnant and Kockelman (2013) expect energy savings by 5%, if the number of de- and acceleration processes can be reduced by 20%. Also vehicle platooning improves aerodynamics and enables fuel and energy savings by 10 to 25% (Fagnant and Kockelman 2014; Morgan Stanley 2013). This pattern however is less relevant for inner-urban traffic where travel speeds are low and aerodynamic resistance negligible. A more relevant effect on urban areas are traffic management systems for AVs that minimize congestion and thus reduce congestion-induced fuel/ energy consumption and emissions (Ticoll 2015). Furthermore, the traffic management systems can be used to avoid excess emission loads (e.g., by particulates) by temporary re-routing of vehicles.

Also advanced vehicle concepts facilitated by autonomous vehicles can reduce fuel and energy consumption. Conventional cars tend to be oversized, because they provide space for four to five passengers, although their average occupancy rate is below two persons per trip (e.g., Hars 2014b). Therefore, conventional vehicles considered as "general-purpose tools" (Hars 2010) can be replaced by AVs specifically designed for certain trip purposes, which tend to be smaller in terms of size and weight compared to conventional cars. Furthermore, equipment such as steering wheel or pedals become obsolete in a fully automated vehicle. Smaller car bodies and less equipment enables to downsize the engine and other vehicle components. Reducing a vehicle's weight by 20% allows a decrease in fuel consumption by 6–7% (Barcham 2014). Anderson et al. (2014) estimated the fuel efficiency of conventional and fully automated (hybrid) vehicles until the year 2050: In 2010, a conventionally driven vehicle had a range of 31–43 miles per gallon (mpg), which is expected to increase to 65–92 miles in 2030 and to 87–145 miles in 2050. Under the assumption that autonomous cars have the same dimensions as conventional ones, the range of autonomous cars is expected to reach 175 mpg with a combustion engine, and 290 mpg with hybrid compulsion. The highest increase in fuel efficiency (up to 300–500 mpg) is expected for fully automated cars in pod design, which are highly appropriate for use in urban areas (Anderson et al. 2014). The future size of AVs will be also determined by their ownership: shared autonomous vehicles are expected to be considerably smaller than conventional cars. However, privately owned autonomous cars may represent luxury limousines and living rooms or offices on wheels (VDV 2015), which is diametrically opposed to downsizing trends and reduction of environmental impacts.

Autonomous vehicles tend to support the transition to electric vehicles. Because of the lower weights of autonomous cars, the storage batteries are lighter, smaller and require less time for charging. Furthermore, since driver and autonomous vehicle are independent from each other, periods of non-use can be used to charge the vehicle. If the electric vehicles are charged with renewable energy, the environmental impact of road transport can be reduced significantly. Simulations of the electric autonomous vehicle fleet by the US Lawrence Berkeley National Laboratory (2013) highlighted a reduction of CO_2 emissions by 87–94% compared to conventional cars in 2015 (Ticoll 2015). With respect of the year 2030, electrically fueled autonomous vehicles are expected to generate 62–82% less CO_2 emissions than hybrid engines (Ticoll 2015).

Summarizing, autonomous vehicles enable fuel savings because of efficient driving style and reductions in size and weight. Their affinity to electrification of road transport results in further environmental benefits, if renewable energy sources are used for the generation of electricity. On the other side, a possible increase in vehicle mileage may generate adverse environmental effects. Furthermore, the ownership of autonomous vehicles is expected to determine their size and weight and thus environmental performance.

3.2.2 Safety

In order to assess the traffic safety enhancement potential by autonomous driving, the determinants of road accidents by conventional driving are important indications. In developed countries the predominant share of road accidents is caused by human errors of the driver (e.g., Winkle 2015), such as use of alcohol or drugs, use of mobile devices during driving (Eugensson et al. 2013; Fagnant and Kockelman 2013), missing driving experience or prolonged reaction times (see Langer, Abendroth and Bruder 2015; Kühn and Hannawald 2015), as well as fatigue or temporary loss of fitness to drive (Langer, Abendroth and Bruder 2015).

Thus in case of entire market penetration by AVs, the impacts on safety are clearly seen positive, since human errors can be omitted (Rodoulis 2014), vehicle performance is not affected by driver fatigue or drivers' emotions (Hars 2010), and it can be ensured that all traffic regulations are met (Fagnant and Kockelman 2013). Intoxicated drivers, posing a severe danger, can be carried safely (Hars 2010). Furthermore, the autonomous vehicle's reaction time and its vast amount of information on traffic situations that can be processed by V2X communication, are superior to human capabilities (Hars 2010).

In quantitative terms, Fagnant and Kockelman (2013) expect a reduction of number of accidents in the USA by more than 80%, if a complete penetration of AVs is attained. Also KPMG (2015) expects a decrease in number of accidents per vehicle by 80% in the period of time 2013–2040, under the assumption that the complete vehicle fleet is fully automated in 2040.

There is overall agreement that a fully autonomous vehicle fleet will considerably improve traffic safety. This pattern is expected for urban areas, too, where – in the European Union – 69% of all traffic accidents occur (EC 2011). Particularly pedestrians and cyclists are concerned by severe injuries and fatalities in accidents in urban areas (Kühn and Hannawald 2015). Autonomous driving is expected to improve traffic safety both for the driver and for pedestrians and cyclists, as through programming of autonomous vehicles the highest priority can be assigned to avoidance of human damage rather than material damage (WSP/ Parsons Brinckerhoff and Farrells 2016). Furthermore, the driving program of AVs will reduce speeds if vulnerable traffic participants are present. Just by paying attention to traffic regulations – in this context particularly speed limits – autonomous vehicles will significantly decrease the number of traffic casualties in urban areas: even if a collision cannot be avoided, the impact speed cannot be above the maximum allowed speed (WSP/ Parsons Brinckerhoff and Farrells 2016).

Nevertheless, reaching the objective of zero accidents is regarded to remain a vision, even with a fully automated vehicle fleet. Autonomous fleets are expected to result in new accident causes, for instance induced by system failures (e.g., Alessandrini et al. 2015; Winkle 2015). Also the possibility to switch AVs to the manual mode will negatively influence the safety gains, since it will lead to "mixed" traffic conditions (e.g., Alessandrini et al. 2015; KPMG 2015).

3.3 User Aspects

3.3.1 User Costs

Autonomous driving is expected to reduce the generalized user costs of transport by allowing AVs to remain in continuous use, by lowering travel times due to increased capacity and less congestion, by reducing fuel consumption and parking fees, as well as by lower insurance fees because of significant decrease in accidents (e.g., Ticoll 2015).

Furthermore, autonomous driving allows the passenger to conduct further activities during the trip such as working, communicating, organizing, sleeping or eating and drinking. Surveys confirm that the passengers of autonomous cars are willing to pay for being able to conduct other activities during a car trip (Fraunhofer IAO and Horváth & Partners 2016; McKinsey Company 2016). The willingness to pay reaches its highest values for activities during travelling which facilitate time savings (McKinsey Company 2016), and increases with trip duration (Fraunhofer IAO and Horváth & Partners 2016). Thus, the outcomes of the surveys demonstrate that autonomous driving will generate user benefits beyond travel time savings and the reduction of monetary costs.

3.3.2 Comfort

A trip in a car implies a considerable strain for the driver, particularly in urban areas where traffic situations tend to be particularly complex. The driver's seating position in a conventional car implicates an inflexible, physically demanding position, while the driver's concentration on the traffic situation and possible frustrations due to congestion and time loss implicates psychological stress (see Bierstedt et al. 2014). According to findings by the Massachusetts Institute of Technology (2013) a car ride in an urban area in a conventional car is for the driver more stressful than a skydive (see Bierstedt et al. 2014). In an autonomous car however, the seating position is more flexible, and alternative activities – also named "true freedom behind the wheel" (Eugensson et al.

2013, p.13) – can be conducted during the trip. Thus the physical and psychological stress involved with driving a vehicle in an urban area are expected to be significantly relieved by autonomous driving.
The use of AVs facilitates comfortable door-to-door services. Passengers can be picked up at and carried to any location. In a shared system, the autonomous car fleet is likely to consist of different vehicle types, facilitating to meet the requirements of a specific use case. After reaching the passenger's destination, the autonomous car will automatically drive to a parking space, or in case of commercial fleets, provide services to other passengers (e.g., Anderson et al 2014; WSP/ Parsons Brinckerhoff and Farrells 2016). Shifting the responsibility to find a parking space from the driver to the autonomous car represents a major comfort improvement for the passenger.

3.3.3 Access to Mobility

Fully autonomous driving will substantially enhance the mobility conditions for societal groups that have reduced access to individual motorized transport services. These societal groups embrace mobility-impaired citizens, children and adolescents, persons with low income (see Ticoll 2015), as well as non-driving, elderly, or people with travel-restrictive medical conditions (Harper et al. 2016). Ticoll (2015) estimates 40% of the population of Toronto belonging to societal groups with restricted access to mobility. Even if a certain share of these societal groups requires further assistance during the journey, the use of fully automated vehicles improves the overall conditions for personal mobility, by providing access to individual mobility services at relatively low costs. Facilitating safe and secure door-to-door trips, these societal groups benefit from improved social inclusion, better economic and social opportunities, personal autonomy and access to essential services and facilities (Anderson et al 2014; Bradburn et al. 2015; Johanning and Mildner 2015).

3.4 Land use

Autonomous driving is expected to reduce the generalized costs of road transport. Lowering the burden and costs of commuting increases the attractiveness of living locations more distant from the city center, which may lead to dispersed land use pattern with low density (see e.g., Anderson et al. 2014; Heinrichs 2015).
On the other hand, autonomous driving will reduce the number of parking places required in urban areas (e.g., Meier-Burkert 2014; Timpner et al. 2015; Wilkens 2015). In case of London – where currently 8,000 hectares are needed only for parking –, fully automated driving is expected to cut the required parking space by 50–70% (WSP/ Parsons Brinckerhoff and Farrells, 2016). Furthermore, parking space is expected to be shifted from urban areas to areas outside the city centers (e.g., Anderson et al. 2014). Finally, certain infrastructure components, such as lanes or curve radius can be downsized (e.g., Eugensson et al. 2013; Rodoulis 2014). A reduction of urban areas used for transport infrastructure opens up new use opportunities, for instance for commercial or residential buildings, or leisure facilities and green spaces (e.g., WSP/ Parsons Brinckerhoff and Farrells 2016). Thus the change of land use in urban areas induced by autonomous driving may enhance the attractiveness of urban areas for living and business.
Summarizing, potential impacts of autonomous driving on urban land use patterns are driven by two opposed aspects: on one hand, decreasing transport user costs support dispersed land use, on the other hand autonomous driving may increase the quality of life in urban areas, thus attracting new residents.

4. CASE STUDIES

4.1 Overview of applied modelling approaches

In this chapter, the results of model simulations are presented for the cities of Brisbane, Lisbon, Austin, Ann Harbor, New York, Singapore and Berlin. For Brisbane, the model simulations have been conducted under the assumption that both fully automated vehicles and conventional vehicles operate in the urban and suburban area ("mixed traffic scenario"). For Austin, Ann Arbor, New York, Singapore and Berlin the simulations refer to fleets which consist of fully automated vehicles only. Lisbon highlights with simulations for both cases (mixed fleets, fully automated fleet only).
For the case studies of New York and Singapore the same modelling approach, a spatial queuing model, was used with different assumptions for each city. For the Ann Harbor case study, approximate analytical tool based on network and queuing methodologies was applied, whose results were verified by applying a simulation model. The scenarios in Brisbane were simulated under application of the TransPostion 4S Model. For Austin, Lisbon and Berlin, agent-based simulation models with different assumptions were applied.

4.2 Brisbane

The first case study uses the TransPosition 4S Model – developed by Davidson (2011) – to analyze the impacts of mixed traffic scenarios in Brisbane (Australia). The Random Utility Maximization Theory (see e.g., McFadden 1974) serves as basis for the model. For the Brisbane Case Study conducted by Davidson and Spinoulas (2015), four different scenarios of mixed traffic situations were simulated and compared to the corresponding reference case, i.e. traffic without AVs. Scenario (1) and (2) assume an AV share of 25%, Scenario (3) and (4) of 75% (Table 1).

Table 1: Scenario assumptions of the Brisbane case study (see Davidson and Spinoulas 2015)

Scenario	AV Share	Value of Time	No. of Trips	Operating Costs
(1) 2021 AVs	25%	-5–25%	+10%	No change
(2) 2021 electric AVs	25%	-5–25%	+10%	-50%
(3) 2031 AVs	75%	-10–50%	+10%	No change
(4) 2031 electric AVs	75%	-10–50%	+20%	-50%

Table 2 shows the modelled impacts of autonomous driving in comparison with the transport system without AVs. The integration of AVs is expected to result in an increase in vehicle-kilometers travelled (VKT), vehicle-hours travelled (VHT), average trip length, and – besides for electric AVs in 2031 – an increase in number of trips. The impacts are more significant for electric AVs, since electric vehicles are assumed to have 50% lower operating costs than conventionally fueled AVs (Table 1). Thus, compared to conventional AVs, electric AVs are expected to significantly increase average trip length, and subsequently VKT and VHT. The increase in VKT in all scenarios – particularly for scenario (2), (3) and (4) – will worsen congestion. Because of the increase in average trip length, especially sub-urban areas will be affected by increased congestion. Therefore, the average speed is expected to decline, notably in 2031. Finally, the market shares of competing modes (public transport (PT), walking and cycling) are expected to drop, especially if AVs are widely adopted and if the cars are driven electrically.

Table 2: Projected key figures for Brisbane's transport system with an AV integration compared to its transport system without an AV integration (in 2021 and 2031) (see Davidson and Spinoulas 2015)

Scenario	Base Case	No. of Trips	Trip length	VKT	VHT	Speed	PT share	Walking/ Cycling share
(1) 2021 AVs	2021	2.5%	1.1%	3.6%	4.7%	-1.0%	1.2%	-0.1%
(2) 2021 electric AVs	2021	3.1%	11.7%	15.1%	15.1%	0.0%	-2.1%	-3.7%
(3) 2031 AVs	2031	8.1%	5.9%	14.5%	24.1%	-7.8%	-1.6%	-3.3%
(4) 2031 electric AVs	2031	-1.9%	34.0%	31.5%	43.4%	-8.3%	-13.6%	-11.0%

In summary, the integration of AVs will increase demand and vehicle mileage. It will also affect congestion, travel times and therefore productivity in a negative way. Trip destinations within the city area tend to be replaced by more distant destinations. Although Davidson and Spinoulas (2015) expect safety and comfort profits, they are of the opinion that Brisbane's traffic situation will at first worsen through the gradual integration of AVs, before it will improve.

4.3 Lisbon

The case study of Lisbon (Portugal) conducted by the International Transport Forum (ITF) (2015) under application of an agent-based model assumes the presence of a system of shared autonomous vehicles (SAV). SAVs are fully autonomous vehicles which can be ordered on-demand, fulfil a customer's transport request and locate themselves according to the predicted demand. The ITF (2015) differentiates between SAV penetration rates of 50% (Scenario (1)) and 100% (Scenario (2)). There are two possible SAV systems: The carsharing system (AutoVot system) and the ridesharing system (TaxiBot system). Carsharing can only be used by just one user at a time while ridesharing offers services for several simultaneously. The ridesharing system allows customers to enter and leave a SAV during a trip. Moreover, the consequences of Lisbon's (partly) autonomous traffic have been analyzed with and without the availability of a high-capacity public transport. If PT it is not available, SAVs take over the half (Scenario (1)) respectively all of its trips (Scenario (2)).

Table 3: Lisbon's fleet size with SAV integration (see ITF 2015)

Base case: 203,000 vehicles		PT	Fleet size	% of base case
100% SAV penetration	Ridesharing	no	25,917	12.8%
		yes	21,120	10.4%
	Carsharing	no	46,249	22.8%
		yes	34,082	16.8%
50% SAV penetration	Ridesharing	no	13,256 + 194,537*	102.4%
		yes	10,900 + 147,767*	78.2%
	Carsharing	no	22,887 + 194,275*	107.0%
		yes	18,358 + 148,050*	82.0%

*****SAVs + Private vehicles

Table 4: Lisbon's travel volume with SAV integration (see ITF 2015)

Base case: 3.8 million km		PT	Car-km [million]	% of base case
100% SAV penetration	Ridesharing	no	4.62	122.4%
		yes	4.01	106.4%
	Carsharing	no	7.15	189.4%
		yes	5.44	144.3%
50% SAV penetration	Ridesharing	no	6.04	160.2%
		yes	4.90	129.8%
	Carsharing	no	7.20	190.9%
		yes	5.69	150.9%

Table 3 illustrates that in a mixed scenario the total car fleet will decrease, if PT is available. In the absence of PT Lisbon's fleet is expected to grow. A homogenous SAV traffic (Scenario (1)) with PT yield the most favorable benefits as nine out of ten cars might no longer be needed (TaxiBot system). Consequently, alternative transport modes as well as a high penetration rate of SAVs are necessary for a significant fleet size reduction.

Even if less cars operate in the Portuguese capital, the total travel volume in the city (Table 4) is affected negatively by the SAV integration. For both scenarios total travel volume is expected to grow considerably, whereas growth rates are generally higher in carsharing than in ridesharing systems. Again, scenario (2) is more preferable than scenario (1) as a mixed traffic situation generates more daily driven kilometers than a fully autonomous traffic system.

Table 5 contains the number of cars circulating on urban roads during the peak hours. In three out of four cases in the mixed scenario more cars will use the urban roads. This pattern appears even worse when considering that Lisbon's transport system has already reached its capacity limit. In 2016, 61% (72%) more travel time was needed during the morning (evening) peak compared to an uncongested traffic situation (TomTom Traffic Index 2016). Hence, if SAVs have a penetration rate of 50% or less, congestion is likely to worsen. In contrast, Scenario (2) leads to a clear decrease of circulating cars in peak hours. Whether the net congestion effect of the simultaneous reduction of cars in peak hours and the travel volume increase will be positive or negative in a fully autonomous traffic is not assessed by ITF (2015).

Finally, Table 6 displays the effects of the SAV system on demand for parking space. Whereas a mixed traffic scenario not necessarily leads to (major) reductions in required parking lots, a fully autonomous traffic is expected to do so significantly. Even in the worst case of scenario (2) – the AutoVot system without PT – all 110,000 off-street and 24,379 (49%) on-street parking lots can be eliminated, freeing up 2.12 km^2 (2.5%) of Lisbon's urban area for alternative use.

Moreover, ITF (2015) anticipates SAVs to enhance road safety, car utilization rate and transport system service quality by reducing wait and travel times. As shown in this section, the SAV penetration rate is decisive for the amplitude of SAV implications.

Table 5: Number of cars in peak hours on Lisbon's roads with SAV integration (see ITF 2015)

Base case: 60,000 vehicles		**PT**	**Number of cars**	**% of base case**
100% SAV penetration	Ridesharing	no	25,867	43.1%
		yes	21,105	35.2%
	Carsharing	no	46,011	76.7%
		yes	33,975	56.6%
50% SAV penetration	Ridesharing	no	13,173 + 57,499*	117.8%
		yes	10,890 + 43,675*	90.9%
	Carsharing	no	22,768 + 57,421*	133.6%
		yes	18,305 + 43,759*	103.4%

*SAVs + Private vehicles

Table 6: Maximum demand of parking lots in Lisbon with SAV integration (see ITF 2015)

Base case: 160,000 parking lots		**PT**	**Required parking lots**	**% of base case**
100% SAV penetration	Ridesharing	no	11,563	7.2%
		yes	8,901	5.6%
	Carsharing	no	25,621	16.0%
		yes	17,110	10.7%
50% SAV penetration	Ridesharing	no	5,928 + 153,122*	99.4%
		yes	4,622 + 116,689*	75.8%
	Carsharing	no	12,705 + 153,330*	103.8%
		yes	9,561 + 116,467*	78.8%

*SAVs + Private vehicles

4.4 Austin

In the third Case Study, Fagnant and Kockelman (2014) and Fagnant, Kockelman and Bansal (2015) examine the impact of the replacement of Austin's (USA) current transport system by a SAV system by developing an agent-based simulation model. The model assumes that all requested trips within a certain area of Austin are carried out by SAVs. With MATsim, 24 hours are simulated to identify impacts of the transition to an autonomous traffic system.

A key impact of SAV integration is a significant reduction of the total number of cars operating in Austin, as only 1,977 SAVs are necessary to fulfil the 57,161 requested trips, resulting in 28.5 trips per day and SAV. Thus, one SAV is expected to replace 9.34 conventional vehicles. Households with lower car utilization rates may resign on purchasing a private car, while households owning more than one car are expected to downsize their private car fleet. Fagnant, Kockelman and Bansal (2015) expect a rapidly growing market share if SAVs enter the market, quickly exceeding the share of taxis and conventional shared cars.

The second favorable feature of a SAV system is its high level of service quality. Under the assumption that trips are requested in 5-minute intervals, the average waiting time is one minute. 94.3% (98.8%) of the customers need to wait less than 5 (10) minutes. If trip requests do not occur in 5-minute intervals, the average waiting time is expected to increase by 2.5 minutes.

SAVs generate additional vehicle mileage by 8%, largely generated by the driverless SAV relocation process.

Table 7: Projected life-cycle emissions of SAVs in Austin (see Fagnant, Kockelman and Bansal 2015)

Environmental impacts	US vehicle fleet average	SAV	Change
Energy use [GJ]	1,230.0	1,064.0	-14.0%
Greenhouse gases [metric tons]	90.1	83.2	-7.6%
CO [kg]	3,833.0	2,590.0	-32.0%
SO_2 [kg]	30.6	24,6	-20.0%
NOx [kg]	243.0	198.0	-18.0%
VOC [kg]	180.0	95.2	-47.0%
PM_{10}	30.2	27.9	-7.6%

Table 7 summarizes the environmental impacts of the SAV scenario, comparing the life-cycle emissions and energy use of an average car of the US fleet to a passenger (sedan) SAV. The life-cycle environmental effects depend on four factors: vehicle operation (VMT-based), vehicle manufacture, parking infrastructure and number of vehicle trips (i.e. number of cold and warm engine starts).

Even though SAVs generate additional 8% VMT, PM_{10} and greenhouse gas emissions are expected to decrease slightly as SAVs drive more anticipatorily and tend to be smaller and thus lighter than average US vehicles. Fagnant and Kockelman (2014) expect the number of manufactured cars not to change significantly, even if less cars are in use. This is because SAVs have to be replaced more frequently as their projected lifetime is shorter because of their considerably higher utilization rate. Due to the frequent fleet turnover, SAVs are always state-of-the-art, allowing for less emissions and energy use compared to the current, inflexible US vehicle fleet. Moreover – as less accidents occur in an autonomous traffic –, SAVs have to be repaired less frequently. The decline in parking demand leads to less traffic searching for parking spaces, thereby reducing congestion. Less parking infrastructure has to be maintained, which provides environmental benefits. The overall number of trips decreases, if the conventional is replaced by an autonomous fleet, as the autonomous fleet operates with less cars. In combination with a decreasing share of noxious cold starts due to higher utilization rates of SAVs, CO and VOC emissions can be reduced considerably.

Summarizing, the estimation illustrates that SAVs can clearly enhance Austin's environmental situation as they emit less life-cycle emissions than average US vehicles.

4.5 Ann Arbor

Burns, Jordan and Scarborough (2013) analyze the AV integration into Ann Arbor's (USA) transport system, the only city referred to in this paper with less than 0.5 million inhabitants. The new mobility system consists exclusively out of coordinated, purpose-built SAVs and is modelled by an approximate analytical tool that is based on network and queuing methodologies. Subsequently, the analytical results are verified by applying a simulation model.

The first aspect analyzed by Burns, Jordan and Scarborough (2013) is the SAV fleet size necessary to perform 120,000 trips per day, both in an average (7 am to 7 pm) and in a peak scenario, while providing an adequate service level. A fleet operating with 18,000 SAVs implicates customer waiting times of 15 (average scenario) or 20 seconds (peak scenario). The SAV fleet is 85% smaller than the current private car fleet and would be in use 75% during average daytime, compared to a utilization rate of 5–10% by today's car fleet. As SAVs are on average idle only six hours a day, parking demand will noticeably decrease. A smaller fleet (14,000 SAVs) leads to unacceptable high waiting times during peak hours, a larger fleet (21,000 SAVs) reduces waiting times negligibly to 12 seconds in both scenarios. To guarantee low waiting times, the SAVs have to relocate themselves after each transport, leading to a growth in total VMT.

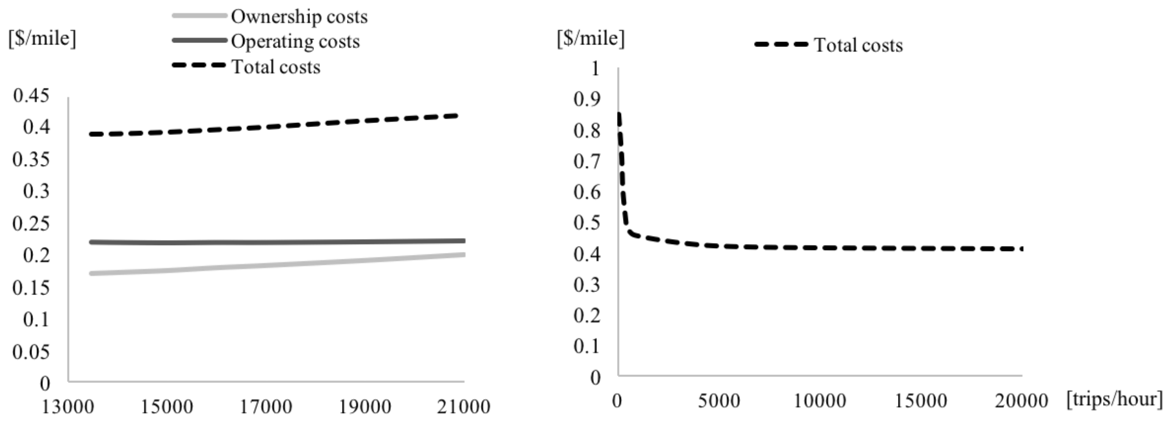

Figure 1: SAV costs per mile for different fleet sizes (left) and a varying number of demanded trips per hour (right) (see Burns, Jordan and Scarborough 2013)

Moreover, the model calculation examines the total costs per mile, differentiated by operating and ownership costs (see Figure 1). While the operating costs remain relatively constant with increasing fleet size, ownership costs rise slightly. The total costs grow with the same rate as the ownership costs. They also vary with the number of trips demanded per hour, if the fleet size is constant.

If less than 1,000 trips are requested within 60 minutes, total costs rise rapidly. The total cost differences within the range of 1,000 to 20,000 trip requests per hour are comparatively small. As economies of scales are reached quickly, even operators of small SAV fleets – which can handle at least 1,000 trip requests per hour – can be competitive.

To benchmark these costs, Figure 2 compares the costs of a conventional car to the ones of a SAV. One mile driven with a conventional car that covers 10,000 miles (15,000 miles) per year amounts to 0.75$ (0.5$). By using a SAV, cost reductions up to 45% (31%) can be realized, mainly due to savings in ownership costs. If the SAV is purpose-built, i.e. optimally configured for the number of customers demanding a journey, further savings by 63% are possible. Due to the fact that in a SAV system both the number of cars and the costs to own and operate them can be reduced considerably, mobility can be provided at significantly lower costs.

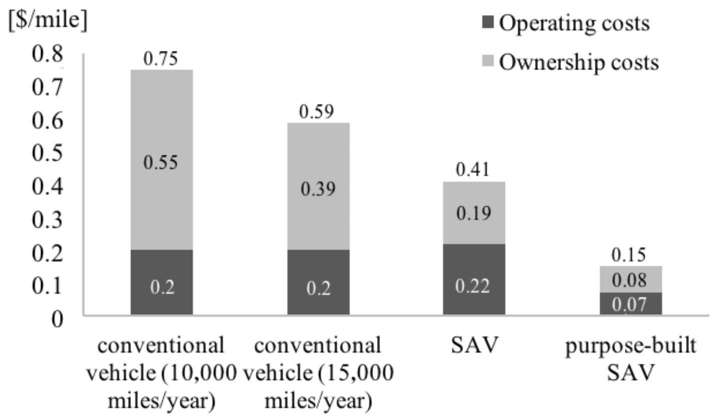

Figure 2: Costs per mile for conventional and shared autonomous vehicles (see Burns, Jordan and Scarborough 2013)

Further advantages expected by Burns, Jordan and Scarborough (2013) are benefits in traffic safety, less congestion, emissions and energy consumption. The value of time decreases, as SAVs enables travel time to be used for alternative activities. Comfort improves as door-to-door transports are offered and parking costs in terms of time and fees no longer exist.

4.6 New York and Singapore

The fifth Case Study deals with SAV systems – referred to as Autonomous Mobility-on-Demand (AMoD) systems by Pavone (2015) – in the cities of New York (USA) and Singapore. Pavone (2015) develops a spatial queuing model for the two AMoD systems. Two approaches for controlling the systems exist. The first one is called “lumped approach” and makes the assumption that transport services are requested at a fixed set of stations within the transport network. In contrast to this discrete method, the “distributed approach” assumes the number of stations to be a continuum, implying that a customer can request a trip at any given point in the network.

To determine the number of small, electrically driven SAVs which can replace the Manhattan taxi fleet consisting of 13,300 cabs (2012), the lumped approach is applied. To ensure a SAV availability of 95%, 8,000 SAVs are necessary in peak hours (7 pm to 8 pm). For a moderate (4 pm to 5 pm) and a low demand (4 am to 5 am) 7,000, respectively 2,000 SAVs are required. To evaluate the service level, waiting times are simulated for fleets that operate 6,000, 7,000 or 8,000 SAVs. In the first case, waiting times amount to over 20 minutes during peak hours. A fleet expansion by 1,000 to 7,000 vehicles significantly improves the service level, as the maximum waiting time drops by more than 75% to under 5 minutes. With a fleet of 7,000 vehicles, a customer has to wait no longer than 2.5 minutes to be picked up by a SAV. These findings indicate that a SAV fleet with 7,000 to 8,000 vehicles can provide high quality mobility while simultaneously guaranteeing high availability. Compared to the taxi fleet, 41%, respectively 47% less cars are sufficient. Pavone (2015) similarly uses the lumped approach to approximate the number of SAVs necessary to replace all 779,890 Singaporean passenger vehicles. A fleet which provides a satisfactory service quality consists of 300,000 SAVs, representing 38% of the current conventional fleet.

Table 8: Mobility costs for the Singaporean AMoD system (see Pavone 2015)

System	Costs per kilometer [$/km]			Costs per year [$/year]		
	COS_i	COT_i	TMC_i	COS_i	COT_i	TMC_i
Conventional (i=1)	0.96	0.76	1.72	18,162	14,460	32,622
AMoD (i=2)	0.66	0.26	0.92	12,563	4,959	17,522

Furthermore, mobility costs for the Singaporean AMoD system (i=2) are examined and compared to the costs of the traditional transport system (i=1) (Table 8). The total mobility cost (TMC_i) comprise the cost of service (COS_i) and the cost of time (COT_i). The first cost unit includes the cost of ownership and operating. The yearly costs of service for AMoD systems amount to about two thirds of the yearly service costs of a conventional fleet. Pavone (2015) estimates the second cost unit – COT_1 (COT_2) – to be 50% (20%) of the median Singaporean wage, as SAV customers do not have to steer manually. Another reason that the time costs for AMoD systems are three times lower than those for conventional systems is the redundancy of parking through SAVs, which significantly saves time. Comparing an AMoD system to the traditional system, it can provide mobility access to Singaporean citizens at almost 50% lower costs.

4.7 Berlin

The implications of an autonomous taxi (AT) fleet of different sizes was conducted by Bischoff and Maciejewski (2016) for Berlin (Germany). The agent-based model is simulated by MATsim and considers all private car trips within the boundaries of Berlin (2.5 million per day).

The simulated fleet sizes range from 50,000 to 250,000 ATs. The authors regard the afternoon peak hour as decisive for determining the fleet size, as the number of requested trips reaches its maximum between 2 pm and 4 pm. Large AT fleets operating 140,000 to 250,000 vehicles are economically unprofitable due to the fact that a high number of ATs are not in use most of the day. Small fleets with 50,000 to 80,000 ATs are not able to satisfy Berlin's afternoon demand which leads to unacceptable waiting times. To provide a high service quality Bischoff and Maciejewski (2016) determine the fleet size to be 100,000 ATs, which implies that one AT replaces ten to twelve conventional vehicles. Although a temporal AT shortage possibly emerges during the afternoon hours, average waiting times are reasonable with around 2.5 minutes. Only during the rush hour, the average waiting times are expected to rise to almost 5 minutes with the 95th percentile waiting up to 15 minutes. Regarding the utilization rate, an AT on average is used 7.5 hours a day and is thus significantly more frequently utilized than a current conventional vehicle (40 minutes). While during afternoon traffic all cars are continually in use, the AT system reveals a low utilization rate in the period of time between midnight and 6 am.

Furthermore, Bischoff and Maciejewski (2016) expect the traffic to be more fluent, if self-driving ATs replace conventional cars. This – in combination with the elimination of parking search related traffic – can possibly compensate the increase in total vehicle drive time (+17%). Finally, the authors emphasize that simulation results will differ from city to city, depending on the specific transport conditions of each case.

5. SYNTHESIS AND RECOMMENDATIONS

For several impacts of autonomous driving in urban areas the literature review – consisting of both model simulations and other studies and literature – has revealed unambiguous reactions (see summary in Tab. 9 and Tab. 10): the size of urban vehicle fleets is expected to decrease, and the utilization rates of autonomous vehicles will be higher than they are with conventional vehicle fleets. Private car ownership is expected to decrease, and the authors expect a higher importance of car sharing concepts. Autonomous driving will result in an enhancement of transport infrastructure capacity. Furthermore, autonomous vehicles have lower weights and have high affinity with the use of alternative engine technologies, facilitating environmental benefits to accrue. Transportation costs are forecasted to decline, and further user benefits occur, since passengers are able to follow other activities during driving. An important benefit of autonomous driving is the considerable improvement of traffic safety.
In terms of access to mobility, autonomous driving will clearly ameliorate mobility conditions for citizens with reduced access to individual motorized transport services.
The impacts of autonomous driving on urban land use patterns are determined by two aspects: on the one hand, decreasing transport user costs that support urban sprawl, on the other, lower demand for parking space that facilitates the conversion of urban areas.
The effect of autonomous vehicles on vehicle mileage represents a key driver: a rise in vehicle mileage has negative impacts on the overall balance of socio-economic benefits by worsening congestion, increasing travel times, as well as affecting environment and safety negatively. A majority of the authors expect a net increase in vehicle mileage, since demand inducing factors (e.g., empty return transports, shift from competing modes, parking outside of city centers, additional demand by new user groups) are expected to outweigh demand reducing factors (e.g., relatively high variable costs of shared systems, decrease in ownership of privately owned cars, less traffic for searching park spaces). Thus, the expected increase in vehicle mileage, raises some uncertainty whether socio-economic benefits inherent to autonomous driving will actually materialize.

Therefore, in order to ensure that the benefits of autonomous driving can actually materialize, urban transport policy is recommended to thwart a significant increase in road vehicle mileage by appropriate policies. According to the literature review elaborated in this paper, following policy challenges for urban (transport) planners can be derived:
(1) Avoiding modal shift from public transport and non-motorized modes to autonomous vehicles: As a comfortable mode of transport, autonomous vehicles are likely to become a potent competitor to public transport systems and – to lower extent – to non-motorized modes. A shift of urban transport demand from public transport and non-motorized modes to road causes unfavorable socio-economic effects. To avoid autonomous vehicles from cannibalizing public transport systems, it is important to ensure that autonomous vehicles become part of a smart urban mobility system, in which they are well integrated with public transport and non-motorized modes.
(2) Fostering sharing systems: Shared fleets of autonomous vehicles reduce the number of road vehicles in the city center, and reduce the number of empty (return) trips. Thus sharing systems support the potential of autonomous driving for converting redundant urban transport infrastructure. Furthermore, compared to privately used fleets, it enables savings in vehicle mileage.

(3) Avoiding urban sprawl: Comfortable and inexpensive mobility services by autonomous vehicles have the potential to make commuting, even for longer distances, more attractive. In order to avoid unwanted land use patterns and an increase in vehicle mileage because of long commuting distances, it is crucial that urban centers are attractive and affordable for living. This can be achieved – among others – by a considerate conversion of redundant transport infrastructure into new ways of utilization.

The review has also revealed several aspects which require further attention by research. The occurrence of socio-economic benefits depends on manifold determinants, particularly critically on the variables affecting vehicle mileage. Thus more research is required to investigate further, how autonomous driving and car sharing concepts will influence individuals' "generalized costs" and subsequently affect mobility behavior in terms of trip generation, trip distribution, mode and route choice. Furthermore, research is needed to identify adequate (transport) policy measures which facilitate a full exploitation of autonomous vehicles' potential to generate socio-economic benefits, counteracting possible adverse developments.

Table 9: Impacts of use of AVs based on model calculations

	Case studies / Impacts	Mixed scenarios		Fully autonomous scenarios					
		2.2	**2.3**	**2.3**	**2.4**	**2.5**	**2.6**	**2.6**	**2.7**
		Brisbane	**Lisbon**	**Lisbon**	**Austin**	**Ann Arbor**	**New York**	**Singapore**	**Berlin**
1	Fleet size		?	–	–	–	–	–	–
	Vehicle utilization rate	+	+	+	+	+			+
	Number of trips	+/–[1]							
	Length of trips	+							
	Vehicle mileage	+	+	+	+	+			
	Speed	–							
	Congestion	+	+		–	–			?
	Share of competing modes	–							
2	Air emissions				–	–			
	Energy use				–	–			
	Road transport safety	+			+	+			
3	Total costs					–		–	
	Ownership costs					–		[–][2]	
	Operating costs	=/–[3]				=/–[4]		[–][2]	
	Time costs							–	
	Travel disutility	–				–		–	
4	Demand for parking space		?	–	–	–			–

1 Traffic 2 Environment and safety 3 User aspects 4 Urban structure + Increase – Decrease = No change ? Uncertain

[1] Number of trips increases for conventional AVs and for electric AVs with a low market penetration (25%), but decreases for electric AVs with a high market penetration (75%).
[2] As service costs (ownership plus operating costs) decrease, either both cost units decrease or one cost unit decreases stronger than the other one.
[3] Operating costs remain constant for conventionally fueled SAVs (=) but decrease for electric SAVs (-).
[4] Operating costs remain constant for mid-sized SAVs (=) but decrease for purpose-built SAVs (-).

Table 10: Impacts of use of AVs based on other literature and studies

	Literature / Impacts	Johanning & Mildner (2015)	Anderson et al. (2014)	Hars (2010)	Hars (2014a)	Eugensson et al. (2013)	Rodoulis (2014)	Litman (2015)
1	Fleet size			–	–			
	Private car ownership rate	–	–	–	–		–	–
	Demand for carsharing	+	+	+	+		+	+
	Vehicle utilization rate			+	+		+	
	Vehicle mileage	+	+					+
	Speed		+				+	
	Congestion	–	?	–	–	–	–	?
	Infrastructure capacity	+	+	+	+	+	+	+
	Share of competing modes	–	–					
2	Air emissions	–	?	–	–	–	–	?
	Energy use	–	?	–	–	–	–	?
	Affinity to alternative propulsion systems		+	+	+			
	Road transport safety	+	+	+	+	+	+	+
3	Total user costs		–	–	–			–
	Ownership costs		–					
	Operating costs		–					
	Time costs		–					
	Passenger productivity during trip	+	+			+	+	+
	Travel disutility	–	–			–	–	
	Access to mobility	+	+	+	+	+	+	+
4	Demand for parking space		–		–		–	
	Urban sprawl		+				+	
	Compression of town centers		+				–	

	Literature / Impacts	Fagnant & Kockelman (2013)	Ticoll (2015)	Kückelhaus (2014)	Brandburn et al. (2015)	Morgan Stanley (2013)	KPMG & CAR (2012)
1	Fleet size	–	+/–[5]				
	Private car ownership rate	–	–			=	
	Demand for carsharing	+					+
	Vehicle utilization rate		+			+	+
	Vehicle mileage	+	?		?	+	
	Speed	+		+		+	
	Congestion	–	–	–	–	–	–
	Infrastructure capacity	+	+		+	+	+
2	Air emissions	?	–	–	?		
	Energy use	?	–	–		–	–
	Affinity to alternative propulsion systems		+				
	Road transport safety	+	+	+	+	+	+
3	Total costs		–				
	Ownership costs		–				
	Operating costs		–				
	Time costs		–				
	Passenger productivity during trip	+	+	+	+	+	+
	Travel disutility				–	–	
	Access to mobility	+	+	+	+	+	+
4	Demand for parking space	–	–				–
	Urban sprawl	–	+			+	

1 Traffic 2 Environment and safety 3 User aspects 4 Urban structure + Increase – Decrease = No change ? Uncertain

[5] Dependent on whether privately owned vehicles or on-demand services prevail.

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