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Effects of driverless vehicles: A review of simulations

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Abstract

The development of driverless vehicles is fast, and the technology has the potential to significantly affect the transport system, society and environment. However, there are still many open questions regarding what this development will look like and there are several counteracting forces. This paper addresses the effects of driverless vehicles by performing a literature review of twenty papers that use simulation to model effects of driverless vehicles. By combing and analysing the results from these simulation studies, an overall picture of the effects of driverless vehicles is presented.

The paper shows that focus in existing literature has been on effects of driverless taxi applications in urban areas. Some parameters, such as trip cost and waiting time, show small variations between the reviewed papers. Other parameters, such as vehicle kilometres travelled (VKT), show larger variations and depend heavily on the assumptions concerning value of time and level of sharing. In general, increases in VKT are predicted for most applications. Ride sharing has the potential to reduce VKT, and thereby energy consumption and congestion, but the analysis indicates that a sufficient level of ride sharing to reduce VKT will not be achieved without incentives or regulations. Furthermore, the VKT of driverless vehicles is unevenly distributed from a time and space perspective, with larger increases in VKT during peak hours than in off-peak, and in the suburbs compared to city centres.

The reviewed papers provide a first prediction of factors such as waiting time, VKT and trip cost, in particular for urban areas and for schemes where there is one service provider present. To get a deeper understanding of the effects of driverless vehicles, aspects such as local spatial considerations, e.g. at pick-up stations, and more complex schemes with competition between service providers should be studied. Furthermore, there is a need for sensitivity analyses regarding travel demand.

Keywords: Driverless vehicle; Automated vehicle; Autonomous taxi; Traffic simulation; Societal effects;

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Introduction

The development of automated driving technology and its use in driverless automated vehicles is fast, and the technology has the potential to significantly affect the transport system, society and environment. However, there are still many open questions regarding what this development will look like and several counteracting forces exist (Pernestål Brenden, Kristoffersson, and Mattsson 2017; Milakis et al. 2017; Townsend 2014). For example, automation may lead to increased road capacity, which reduces congestion. On the other hand, the possibility to use the time in the car for other things than driving, lower marginal travel costs and new user groups may lead to increased traffic (Litman 2015). The societal effects of driverless vehicles do not come directly from the technology itself, but rather from how it is used (Barth, Boriboonsomsin, and Wu 2014; Brown, Gonder, and Repac 2014; MacKenzie, Wadud, and Leiby 2014) and there is still a lack of understanding how the contradicting forces interact.

To obtain quantitative estimations of system effects, simulation models[1] can be used. Using simulation models, the effects of specific variables, such as trip cost, fleet size, and travel demand, can be investigated. Operational simulation models have become more and more sophisticated during the latest decades and heterogeneous individuals and complex interactions can now be simulated, e.g. using agent-based models (Bonabeau 2002; Duncan 2010). However, setting up such simulation models is a complex task, and typically a large amount of data and time effort is needed to calibrate these models. The data can be challenging to collect, in particular data on the effects of automation as such systems do not exist yet. Also, for many simulation models, run time is dependent on the size of the network and the complex interactions between some variables, and therefore assumptions, such as fixed travel demand, are often made to reduce run time and the complexity of the simulation. The models are thus built for specific areas and are in general used for case studies. Therefore, the results from a single simulation model may be difficult to generalize.

In the literature there are a number of simulations studying different aspects of effects of driverless vehicles. Each of these simulation studies can be seen as a case study. By reviewing the simulation studies, comparing them, and acknowledging that they describe different cases, the aim of this paper is to achieve a holistic picture of the effects of driverless vehicles. By using this approach, the paper addresses questions such as: Which type of application areas and mobility concepts are covered by the existing simulation studies? What are the effects on performance indicators such as trip cost, vehicle kilometres travelled (VKT), fleet size, waiting time etc.? What are the existing research gaps?

Methodology

This literature review uses Wee and Banister (2016) as methodological framework. Database searches in combination with forward and backward snowballing (Jalali and Wohlin 2012) have been used as search strategies to find relevant papers. The search was performed with the keywords "autonomous vehicle(s)" and "driverless vehicle(s)" combined with "impact AND service", "taxi", "fleet size" and "model" in title, abstract and keywords were used as search terms in Scopus (www.scopus.com) and Google Scholar (https://scholar.google.com). This initial search resulted in a set of fifteen papers considered relevant for the scope of this literature review. With these papers as a base, another five relevant papers were found via backward and forward snowballing. Thus, the literature search resulted in twenty papers reviewed in this article.

A number of criteria were applied in selection of relevant papers. First, this review is limited to passenger transport. Second, it considers only conditionally or fully driverless vehicles, i.e. driverless vehicles of SAE level 4 operating only in its operational design domain or driverless vehicles of SAE level 5 (SAE International 2016). Third, papers have only been selected if they conduct numerical simulations of travel demand or traffic flow. Fourth, only papers that present results on a *network level* have been selected. There are a number of papers, see e.g. (van den Berg and Verhoef 2016; Ye and Yamamoto 2018), that study the effects of driverless vehicles on traffic flow and capacity on a road segment (e.g. a motorway link), but these are excluded from this review. Also within the chosen set of papers there are limitations in the review. Even though some of the chosen papers evaluate different dispatch strategies, there is no intention to try to compare effects of different dispatch strategies. Rather, focus of this review is on system effects such as vehicle kilometres travelled, fleet size, and waiting time.

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[1] For simplicity, simulation model is used in its broadest sense in this paper and encompasses both analytic and simulation-based transport models.

To make an overview of the reviewed papers, nine dimensions are selected: simulation approach, scale of application, mobility concept, penetration rate, travel demand, trip cost, vehicle kilometres travelled, fleet size, and waiting time (see Table 2). The first five dimensions are chosen to compare the set-up of the simulation studies. The other dimensions are chosen to compare reported effects of driverless vehicles. The result dimensions are chosen by identifying which are the main variables for which results are reported in the reviewed papers.

The comparison goes beyond these nine dimensions, and also other aspects such as geographical and behavioural aspects are discussed. In the paper, analysis and synthesis are used to extract new knowledge from the full set of reviewed papers, in order to take one step further compared to solely discussing results of individual papers.

The reviewed papers

The literature search resulted in twenty selected papers. Out of the nine dimensions chosen for the overview, the first five (simulation approach, scale of application, mobility concept, penetration rate and travel demand) describe the simulation study, i.e. the model set-up for the case studied. The remaining four dimensions (trip cost, vehicle kilometres travelled, fleet size and waiting time) represent effects of driverless vehicles. These particular dimensions were chosen because they are the four most frequently reported simulation result dimensions in the reviewed papers. There are also other dimensions, e.g. parking demand, modal choice and energy consumption that are relevant, and which are also discussed in this review paper, but there were not enough papers treating these dimensions to include them as columns in Table 2.

Dimensions for comparison

Different **simulation approaches** are used in the reviewed papers in order to study the effects of driverless vehicles. The classification of simulation approach in this paper follows the level of detail classification of Hoogendorn and Bovy (2001), who categorize transport models in five dimensions: scale of the independent variables (continuous, discrete, semi-discrete), level of detail (sub-microscopic, microscopic, mesoscopic, macroscopic), representation of the processes (deterministic, stochastic), operationalization (analytical, simulation) and scale of application (networks, stretches, links, and intersections). The level of detail of the simulation approaches in the reviewed papers ranges from sub-microscopic, via microscopic and mesoscopic to macroscopic. Note that sub-microscopic simulation is sometimes also called agent-based simulation or nano-simulation (Duncan 2010). Sub-microscopic models are at the highest level of detail and simulate travellers as they choose mode and route in the network. On a slightly coarser level, microscopic models simulate individual vehicles and their routes in the network, assuming a fixed mode choice. Macroscopic models on the other hand, simulate flows of vehicles and how link travel times vary with link flow.

The **scale of application** describes the size of the area studied in the simulation. Comparing to the scale of application classification of Hoogendorn and Bovy (2001), only networks and stretches are relevant for this paper. Therefore, networks are further classified into city centre networks, small city networks, large city networks, region/state networks and country networks. If information exists, the scale of application is also described by the size of the studied area in square kilometres, number of inhabitants in the studied area and time-period for the simulation.

Mobility concept refers to the type of operation the driverless vehicles are used for. The nomenclature for mobility concept is not consistent in literature. In particular, terms such as “automated”, “autonomous”, “self-driving”, and “driverless” vehicles are used in the literature. To stress that this review focuses on vehicles without a driver, i.e. SAE levels 4 and 5, the term “driverless” is chosen in this paper. To be able to compare mobility concepts across reviewed papers, the definition presented in Table 1 is used throughout this paper. This means that the nomenclature used in this paper may deviate from the nomenclature in the original papers. However, the interpretation of the service is the same.

Table 1: Nomenclature for mobility concepts.

Abbreviation	Description
CDC	Conventionally Driven Car. Privately owned, manually driven.
PDV	Privately owned Driverless Vehicle. Can be shared within the family.
DT	Driverless Taxi (up to 6 passengers). Vehicles are operated as a fleet. Shared vehicles, but not shared rides.
SDT	Shared Driverless Taxi (up to 6 passengers). Vehicles are operated as a fleet. Shared vehicles and shared rides.
SBDT/SBSDT	Station Based DT/SDT. DT or SDT that operates between stations or defined pick-up points, i.e. the travellers must walk to the stations to start their ride.
DB	Driverless Bus (> 6 passengers). Shared vehicles and shared rides.

Penetration rate refers to the share of trips in the simulation study that is performed with driverless vehicles using any of the mobility concepts described above. In one case (W. Zhang et al. 2015), penetration rate refers to the share of agents using driverless cars rather than the share of trips. What type of trips are replaced by driverless cars differ in the papers. The type of trips replaced are therefore also stated in the penetration rate column, e.g. per cent of private car trips/public transport trips/taxi trips/all trips.

Travel demand is the number of person trips included in the simulation study. It can be given as input data and assumed to be fixed, or it can be modelled using choice models and thus an output. The travel demand also provides an indication of the size and the length of the scenario modelled.

Trip cost is here the marginal monetary cost of driving for car trips, i.e. not including the cost for buying the car. For public transport, trip cost is the same as ticket price. In Table 2, trip cost has been translated to Euro by using the exchange rate of $1 = € 0,845.

Vehicle kilometres travelled (VKT) is the total sum of all kilometres travelled by vehicles during the simulation time, including both empty and occupied kilometres. In Table 2, VKT is presented as a change in percent. As the base line scenario varies between the papers (some use e.g. VKT by CDC as a base line, while others use a certain mobility concept), a brief description of the reasons for the change is also provided. The reasons for VKT changes in the reviewed papers are: that driverless vehicles drive without passengers to pick up the next passenger or to go to a parking place (called “empty kilometres” in Table 2), that they drive empty to relocate in a speculative manner to reduce waiting time for potential future passengers (called “relocation” in Table 2), and due to changes in ride sharing schemes, mode shares and trip generation.

Fleet size is either expressed as the number of vehicles used in the service, or as the number of CDC or conventional buses one automated vehicle replaces. Explicit numbers of the fleet size provide an indication of the size of the application to be modelled.

Waiting time is an output from most of the simulation studies and indicates service level. It is given in minutes or as a percentage of current bus or car travel time.

Overview of the simulation studies

In Table 2, papers are arranged by the size of the areas studied, ranging from a single line to a whole country. As the different simulations have different intentions, the parameters, inputs and outputs used vary. Regular style indicates values that were given as input or used as parameters in the simulation and italic style indicate simulation outputs. If there are several mobility concepts studied in one paper, they are marked with (a), (b) etc. In most papers, simulations are performed with several different parameter settings. However, as Table 2 is only an overview, the aim here has been to identify the main results of each paper rather than presenting all results. Specific results and perspectives that are not covered in the overview table are further discussed in Section 4.3. In Table 2 percentage values have been rounded to the nearest integer and time values to the nearest tenth of a minute.

Table 2: Overview of the reviewed simulation studies. Regular style denotes input values or parameters set in the papers, and italic style represent outputs or simulation results.

#	Author	Simulation approach	Scale of application	Mobility concept	Penetration rate	Travel demand	Trip cost	Vehicle kilometres travelled	Fleet size	Waiting time
1	Winter et. al (2016)	Microscopic	Stretch Predefined line 7 km in The Netherlands 1 day	DB (10 passengers)	100% of all trips for the given road stretch	3 693 trips for 1 day	*1.95 €/passenger = 0.23 €/km*	-	*N = 224*	*2.2 min*
2	Dia and Javanshour (2017)	Sub-microscopic	City centre network 6 km^2 Melbourne Trips within the area 07:00-09:00	(a) PDV (b) PDV (25%) + DT (75%)	100% of private car trips within the area	*(a) 2 136 trips* *(b) 2 059 trips* *for 2h*	-	*(a) +29%* *(b) +10% due to empty km and relocation*	*(a) N = 1217, 1 PDV = 1.75 CDC* *(b) N= 24, 1 DT = 8.3 CDC*	*(a) 0 min* *(b)1.0 min*
3	Azevedo et. al (2016)	Sub-microscopic	City centre network 14 km^2 Singapore Trips within the area 03:00 – 15:00	SDT	100% of all trips. No private cars allowed within the area	40 080 trips for 12 h	40% of CDC taxi	-	*N = 2400*	*5 min*
4	Marczuk et. al (2016)	Sub-microscopic	City centre network 56 km^2 Singapore, trips outside truncated 03:00 – 24:00	DT	100% of all trips except subway trips and public buses	363 859 trips for 15 h	-	-	*N = 25000-35000, 23-28% decrease due to relocation*	*10 min*
5	R. Zhang et. al (2015)	Macroscopic	City centre network Manhattan Three time-periods 04:00-05:00 16:00-17:00 19:00-20:00	SBDT	100% of taxi trips within the area	1 982 trips (low) 16 930 trips (average) 29 485 trips (high) for 1 hour	-	-	*N=8000 (70% of conventional taxi fleet)*	*2.5 min*
6	W. Zhang et. al (2015)	Sub-microscopic	City centre network 10x10 miles Artificial gridded city 1 day	SDT	2 % of agents, 100% of all trips of these agents	37 900 trips for 1 day	0.13 -0.21 €/km	*+15-60% due to empty km and relocation*	*N = 650-800, 1 SDT = 14 CDC*	*2.3 min (no relocation)* *1.7 (relocation)*
7	Fagnant and Kockelman (2014)	Microscopic	City centre network 10x10 miles Artificial gridded city Trips < 15 miles	DT	4 % of private car trips	*60 551 trips for 1 day*	-	*+5% (no relocation)* *+11% (relocation)*	*N = 1688, 1 DT = 14 CDC*	*< 20s*

			1 day							
8	Hörl (2017)	Sub-microscopic	Small city network Artificial city 84 000 inhabitants Peak hours 07:00-10:00 and 16:00-18:00	(a) DT (b) SDT in competition with car, bus, walk	*(a) 46%* *(b) 37%* *of all trips*	-	(a) 0.47 €/km (b) 0.243 €/km	*(a) +28%,* *(b) +31%* *due to empty km*	(a) N = 1000 (b) N = 1000	*(a) 4.6 min* *(b) 3.8min*
9	Merlin (2017)	Sub-microscopic	Small city network Ann Arbor 120 000 inhabitants 1 day	(a) DT (b) SDT	100 % of PT trips	-	*(a) 0.51 €/km* *(b) 0.23 €/km*	*(a) 1200% of bus VKT* *(b) 500% of bus VKT*	*(a) 1 bus = 12.3 DT (N=800),* *(b) 1 bus = 6 SDT (N=400)*	*(a) 5.6 min* *(b) 5.9 min* *(bus 6.2 min)*
10	Burghout et. al (2015)	Microscopic	Large city network Stockholm 2 million inhabitants 1 day	(a) DT (b) SDT	100% of private car trips	271 868 trips for 1 day	-	*(a) +24%* *(b) -24%* *compared to CDC, due to empty km*	*(a) 1 DT = 12 CDC* *(b) 1 SDT = 20 CDC*	*(a) 0 min* *(b) 8.4min*
11	Bischoff and Maciejewski (2016b)	Sub-microscopic	Large city network Artificial city based on Berlin 1 day	DT	100% of private car trips within the city	2.5 million trips For 1 day	-	*+16% due to empty km*	*N= 100000,* *1 DT = 10 CDC*	*2.3 min*
12	OECD International Transport Forum (2015)	Sub-microscopic	Large city network Lisbon 1 day	(a) DT (b) SDT	(a) 50% of private car trips 100% of public transport trips (b) 100% of private car trips 100% of bus trips	-	-	*(a) + 91% due to empty km, relocation, replacement of metro and buses* *(b) + 6% due to empty km, relocation, replacement of buses*	*(a) 107% of their baseline fleet (CDC)* *(b) 10.4% of their baseline fleet (CDC)*	*(a) 3.3 min* *(b) 3.8 min*
13	Shen and Lopes (2015)	Sub-microscopic	Large city network New York City 1 day	DT	100% of taxi trips	~340 000 trips for 1 day (2013 taxi data)	-	-	N = 12216	*6.3 min (77% of CDC taxi)*

14	Dandl et. al (2017)	Microscopic	Large city network Munich (within area) 05:00-11:00	DT	10% of private car trips	40 000 trips for 6 h	-	*+10 % due to empty km*	N = 4000	*~5 min*
15	Chen and Kockelman (2016)	Sub-microscopic	Large city network 100x100 miles Artificial gridded city 1 day	DT in competition with car and PT	*14-39% of all trips*	*3.6-4.3 million trips for 1 day*	0.39 – 0.53 €/km	*+ 7-9% due to empty km*	*N = 84945, 45,9 trips/vehicle & day*	*3.1 min*
16	Chen et. al (2016)	Sub-microscopic	Large city network 100x100 miles Artificial gridded city 1 day	DT	10% of all trips	680 000 trips for 1 day	*0.22-0.25 €/km (occupied km)*	*+ 7-14% due to empty km, charging, relocation*	*N=2245* *N=2389-39593 depending on charging needs*	*7.7-9.5 min*
17	Brownell and Kornhauser (2014)	Sub-microscopic	Region/State network New Jersey 1 day	SDT (two different sharing schemes)	100% of all trips	32 million trips for 1 day	*0.22- 0.39 €/km*	*-19% due to improved sharing scheme, compared with other SDT application*	*N = 1,61 - 4,45 million*	max 5-7 min
18	Childress et. al (2015)	Sub-microscopic	Region/State network Puget Sound region Washington state 1 day	(a) PDV in competition with walk, PT (b) DT in competition with walk, PT	*(a) 43-45%* *(b) 29%* *of all trips*	*(a) 4.1-4.3* *(b) 4.1* *trips per person*	(a) Same as for CDC (b) *0.87 €/km*	*(a) 4 – 20% compared to CDC, due to parking at home, new trips* *(b) -35% compared to CDC, due to lower mode share*	-	-
19	Davidson and Spinoulas (2016)	Mesoscopic	Region/State network Southeast Queensland 1 day	(a) PDV (b) DT (c) SDT In competition with walk, public transit, CDC	(a) 62% (b) 100% (c) 100% of private car trips	(a) +15% (b) +10% (c) +15% compared to CDC trips	Operation cost 50% of CDC	*(a) +36%* *(b) -8%* *(c) -9%* *due to changes in travel demand.*	-	-
20	Meyer et. al (2017)	Macroscopic	Country network Switzerland 1 day	(a) PDV (b) DT	(a) 100% of car trips (b) 100% of car trips + 100% of public transport trips	-	-	*(a) 69% due to new trips and empty km.* *(b) 15-195% depending on region, due to empty km and new trips*	-	*Accessibility increase:* *(a) +10%* *(b) + 1%*

Analysis

This section provides an analysis of the reviewed papers including the dimensions selected in Table 2, as well as other dimensions. Thus, this analysis is based on the full papers and not only on the overview presented in Table 2.

Which applications are studied?

The scale of application in the reviewed papers span from a 7 km road stretch in the Netherlands to the whole road network of Switzerland. The spread is also large for travel demand, which varies from a few thousands to several millions of trips. Also, the simulated time-period varies in the papers from 1 hour up to a full day (24 hours).

There is a substantial bias in which applications are studied in existing literature. Figure 1 illustrates the distribution of the reviewed papers over the dimensions mobility concept versus scale of application. The figure shows that focus in existing literature is on larger cities or parts of larger cities (e.g, Fagnant and Kockelman (2014) and Dia and Javanshour (2017)). Also, there is a bias towards studies of the mobility concept DT, and to some extent SDT. One single paper simulates a driverless bus system (Winter et al. 2016) and one single paper looks into the effects for a whole country (Meyer et al. 2017).

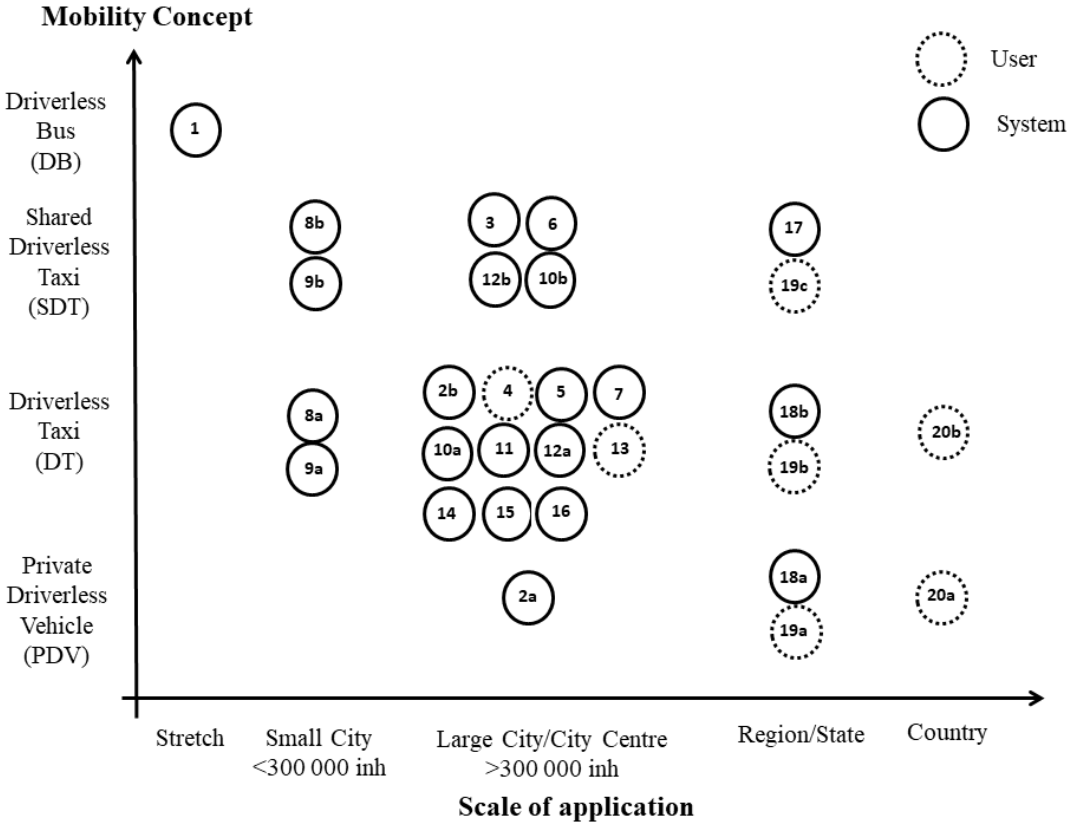

Figure 1: Distribution of the simulation studies across mobility concept and scale of application for the reviewed papers. Solid circles denote studies that optimize from a systems' perspective and dotted circles studies that optimize from a users' perspective.

One conceptual difference between the simulations is who is in focus in the optimisation, the individual user by minimizing waiting time or the system operator by minimizing fleet size and operational cost. Figure 1 shows that the system operator is in centre of the optimisation in most of the studies (e.g. R. Zhang et. al (2015) and Bischoff and Maciejewski (2016b)).

When comparing simulation approach it can be seen that most of the simulation studies in this review take a sub-microscopic approach (e.g. Shen and Lopes (2015) and Hörl (2017)). One likely reason that a sub-microscopic approach is chosen in so many of the papers is that many of the studies require simulation of agents and how they are transported in the network, allowing also for several agents to use the same driverless vehicle. Furthermore, driverless vehicles do not fit very well into the conventional division into car and public transport modes, and the model needs to be flexible enough to allow for this new type of mode which is in-between a private and public mode.

Regarding penetration rate, most of the reviewed simulation studies assume either that all private car trips or all taxi trips within the area are replaced by driverless vehicle trips. Two exceptions are for example Chen et al. (2016) and Dandl et al. (2017) who assume that 10% of car trips are replaced by DT. A couple of papers include a mode choice model (e.g. Chen and Kockelman (2016) and Childress et. al (2015)), and the share of driverless vehicles is then a result of the simulation.

Which are the main reported effects?

In this section, the effects of driverless vehicles from the perspectives presented in Table 2, i.e. trip cost, VKT, fleet Size, and waiting time, are analysed.

Trip cost

The reviewed papers present two major ways of calculating trip cost: based on vehicle related operational costs (Brownell and Kornhauser 2014; Chen, Kockelman, and Hanna 2016; Chen and Kockelman 2016; Winter et al. 2016; Merlin 2017) or assuming a price estimated to be a fraction of the cost for conventionally driven cars and taxis (Azevedo et al. 2016; Childress et al. 2015; Davidson and Spinoulas 2016; R. Zhang et al. 2015).

For DT, the estimated trip cost based on operational costs spans from 0.39-0.53 €/km in most papers. Chen et al. (2016) estimate the cost per occupied kilometre to €0.22-0.25, but does not include the cost for empty kilometres. Childress et al. (2015) assume that the price for DT will be similar to the price for Uber and give the higher estimate 0.87 €/km. For SDT, the price per km spans between €0.13-0.39, with a bias towards numbers around €0.23. The estimated price for DB is around 0.23 €/km.

In the cost calculations, the cost for automation of a vehicle (a cost estimate that spans from €21,000 to €84,500 in the reviewed papers) is considered. Also costs for maintenance, tires and fuel/electricity are taken into account. However, Gawron (2018) show that energy consumption for driverless vehicles may increase with up to 35% compared to CDC due to computations and data transmission, a fact that will affect both the trip cost and the environmental effects. Such increases are not considered in the reviewed papers. Furthermore, the reviewed papers focus primarily on the vehicle related costs, but for DT and SDT services there will also be costs related to the fleet management and the booking/ticketing systems that are not fully considered. In particular, cleaning to keep shared vehicles at a sufficiently high standard can be costly (Bösch et al. 2018).

Childress et al. (2015) discuss that transforming from car ownership to using mobility services such as DT or SDT decreases the investment cost for the user, but increases marginal costs per trip. Davidson and Spinoulas (2016) argue that modal choice is primarily based on the marginal cost per trip rather than the total costs, and show that travel demand will be reduced for DT/SDT services compared to CDC and PDV.

VKT

VKT relates to energy consumption and is thereby connected to emissions and environmental effects. It also relates to utilization of the street space, as the streets will be more crowded if there are more vehicles driving around.

For PDV and the most common assumption that "all cars are driverless", there is an increase in VKT of 20-70% (Childress et al. 2015; Dia and Javanshour 2017; Meyer et al. 2017). The span depends primarily on the difference in assumptions regarding demand increase and on empty kilometres. Demand changes depend on assumptions about new user groups, increased capacity, and reduction in value of time (VOT), while empty kilometres depend on assumptions on where parking is performed and on sharing within the family.

For most DT services the increase in VKT is about 5-30%, with a bias towards around 10%. The changes are primarily due to empty kilometres and relocation of vehicles. Zhang et al. (2015) reports a VKT increase of up to 60% due to a relocation strategy that allows for extensive cruising in order to reduce parking demand. OECD International Transport Forum (2015) report an even higher VKT increase of 90%, primarily due to relocation and that the DT system is assumed to replace all public transport except high capacity modes such as metro, light rail and trains. On the other hand Childress et al. (2015) report a VKT decrease of about 35% as an effect of the reduced demand due to a relatively high price for the DT service compared to other modes.

For SDT, the picture is more diverse, and results span from -25% to +30% compared to CDC. If all rides that, under some constraints on service level, can be shared are shared, significant decreases in VKT can be achieved for SDT in comparison with DT (Burghout, Rigole, and Andreasson 2015; OECD International Transport Forum 2015; Merlin 2017). On the other hand, if a choice model based on trip cost and VOT is used to let agents decide on their mode, a lower percentage of shared rides is achieved (Hörl 2017). This gives VKT in the same range as for DT. These results indicate that there is a potential to reduce VKT by using SDT, but the direct travel cost reductions due to sharing are not sufficient to achieve this potential. Merlin (2017) shows an increase in VKT as large buses are replaced with several smaller vehicles. Meyer et al. (2017) show an increase in VKT due to an increased demand.

Penetration rate has a significant impact on VKT for SDT (OECD International Transport Forum 2015). On the other hand, penetration rate has smaller impact on VKT for DT. This suggests that SDT need a higher travel demand, which in turn mean more trips that overlap in time and distance to be effective.

One effect of increased VKT is congestion or reduced traffic flow. In most papers, this effect is not considered, while some papers handle it by reducing network speed (Fagnant and Kockelman 2014; W. Zhang et al. 2015). Bischoff and Maciejwski (2016b) argue that the increase in VKT is met by improved traffic flow and reduced search for parking, while Meyer et al. (2017) show that for the DT application, congestion may increase significantly in downtown regions, despite assumptions on increased capacity. Dandle et al. (2017) show that if 10% of the private car trips in Munich are replaced by DT, this would lead to a 10% increase in VKT, which causes a delay of private vehicles of about 1%. However, it should be noted that travel time delay is a non-linear function of traffic volume and that it thus makes a large difference if VKT is increased in a network with traffic volumes already close to the capacity limit (May 1990).

The VKT are not evenly distributed in space or time. Empty kilometres will be less than average in city centres and significantly above average in the suburbs (Bischoff and Maciejewski 2016a). Furthermore, VKT increases during peak hours is around double the average VKT increase (Bischoff and Maciejewski 2016b). These effects might cause congestion in new areas in the city outskirts. It will also add more traffic during the already congested peak hours.

The driverless technology is also expected to reduce congestion by increasing road capacity, primarily on freeways. Assuming a 30% capacity increase on freeways due to the driverless technology in the PDV mobility concept, result in accessibility increases of 10-17% (Childress et al. 2015; Meyer et al. 2017).

Fleet size

Fleet size spans from a few hundred to several millions of vehicles in the reviewed papers. When replacing CDC with DT or SDT services the required fleet size reduces substantially. Most papers present results in the order of 1 DT/SDT = 8 - 14 CDC. One exception is Burghout et al. (2015) who show that 1 SDT can replace 20 CDC. The main reason for this is the high level of sharing provided by waiting times and additional travel times that are longer than in the other papers. Different types of relocation strategies have an impact on fleet size, and Marczuk et al. (2016) show that predictive relocation can decrease the fleet size with 23-28%.

Merlin (2017) investigates the scenario when DT/SDT services replace public transport buses. In this case 1 bus = 12 DT/6 SDT, while at the same time VKT also increases with the same order of magnitude, and the traveller waiting time decreases with around 30%. These results indicate that if the energy consumption of a DT or SDT is around 1/12 or 1/6 respectively, it may be a sustainable choice to replace public transport buses with DT/SDT systems.

Waiting time

Most of the reviewed papers use an upper bound on the waiting time to adjust the fleet size. The waiting times spans from around 1-10 minutes, with most simulations at around 3-6 minutes. In some applications, if trips cannot be served within maximum waiting time, the trips are left unserved (Chen, Kockelman, and Hanna 2016; R. Zhang et al. 2015). If the DT/SDT service is expected to replace privately owned cars this is not a realistic assumption, and it would lead to reduced trust in the service.

For a given demand and scale of application, waiting time is dependent on the fleet size, but there is a point where the fleet size is enough to serve the demand. Adding more vehicles after that point does not improve waiting time (Azevedo et al. 2016; W. Zhang et al. 2015). Also penetration rate has an impact on waiting time, in particular for SDT services (OECD International Transport Forum 2015). Relocation of empty vehicles, where vehicles move in a speculative manner to come closer to potential customers, has a positive impact on waiting time (W. Zhang et al. 2015). On the other hand, relocation increases VKT.

Which other effects are discussed?

There are also several effects of driverless vehicles that are discussed in only a smaller subset of the reviewed papers. These are analysed in this section.

Land use

Parking demand can, as a consequence of reduced number of vehicles in the DT and SDT services, be reduced by around 83-94% (Dia and Javanshour 2017; OECD International Transport Forum 2015; W. Zhang et al. 2015). OECD International Transport Forum (2015) show that penetration rate is important for parking demand. For 50% penetration of driverless vehicles, the parking demand spans from 76-104% of the 2015 needs (depending on the presence of public transport), while for 100% penetration the parking demand is about 6-16% of the 2015 needs. These differences primarily depend on that for a lower penetration rate there will be a larger total fleet size due to the co-existence of conventional cars and DT vehicles. Parking demand is not dependent on the willingness to share rides, and is higher in areas that attract trips, e.g. in city centres (W. Zhang et al. 2015). Dia and Javanshour (2017) show that if CDCs are replaced with PDVs that return back to home for parking, the area required for parking can be reduced with 58%. However, this comes with the cost of increased VKT.

The land use needed for **stations and hubs**, including parking for idle vehicles and pick-up/drop-off zones, is only briefly touched upon in some of the papers, and there are in general no reports on the number of vehicles that are located at the same station or parking at the same time.

Geographical differences

Bischoff and Maciejewski (2016a) show that both waiting time and empty kilometres will be larger in the suburbs than in the city centre, a factor that could lead to increased urbanization and movement to city centres. Contrary, the simulations by Meyer et al. (2017) show that accessibility is expected to decrease with up to 29% in city centres, while it increases with more than 28% in some "well connected suburbs" both for PDV and DT, results that may lead to increased attraction to suburbs and thereby increased urban sprawl. The main difference between the papers is that Meyer et al. (2017) takes an increased travel demand into account, while Bischoff and Maciejewski (2016a) use today's demand. In general, there is a tendency that increases in traffic, parking demand and congestion are enhanced in city centres (Bischoff and Maciejewski 2016a; Meyer et al. 2017; W. Zhang et al. 2015).

Energy consumption

One paper (Merlin 2017) considers CO2/ green-house gas emissions. However, these comparisons are very sensitive to the assumptions made about the vehicle fleet (Greenblatt and Saxena 2015; Gawron et al. 2018), and such computations should therefore be seen as hypothetical possibilities.

Travel behaviour

W. Zhang et al. (2015) and Hörl (2017) show that if travellers are given the choice to share a ride or not, around 6-13% of the trips are shared. Based on the fraction of overlapping rides, i.e. rides that can be shared, a higher level of sharing is expected. The reason for the low share is higher that VOT is higher for shared rides, while at the same time as travel time and travel time variance increase. This leads to a resulting generalized time cost for the traveller which in most cases is not compensated by the reduced travel cost. Under plausible variation of VOT (50-110% of private car VOT) and travel cost, the share of DT (in competition with walk and public transport) varies between 14-39%. DT takes mode shares from CDC primarily due to changes in VOT and from public transit primarily by competing with price (Chen and Kockelman 2016). With low VOT for and easy access to PDV, mode shares are primarily taken from walk

(Childress et al. 2015). Winter et al. (2016) optimize the fleet size taking both VOT and operational cost into account, which result in many vehicles and short waiting times.

Areas for future research

The reviewed papers give a good first estimate of the likely effects of driverless vehicles, especially regarding effects on trip cost, VKT, fleet size and waiting time, but also to some extent of the effects on land use, geographical differences and travel behaviour. This section identifies important areas for future research.

One factor that will have an impact on the attractiveness of the mobility concept for driverless vehicles is the travellers' experiences at pick-up and drop-off stations, in particular for DT and SDT based services. However, these stations are generally not investigated in the reviewed papers. Important aspects to study include, but are not limited to: spatial studies/urban form (is there space for the stations within the city?), passenger experience (how many vehicles will there be at each station? If there are more than around 10 vehicles it may be difficult for passengers to find the right vehicle, a fact that could decrease the service level), and traffic flow (if pick-up and drop-off is assumed to be at the streets, how will that affect the traffic flow?).

Another important area for future research is driverless vehicles as a complement to public transport. Driverless vehicles in form of a feeder service to public transport is a mobility concept that has been identified in the literature as relevant and promising from a sustainability perspective (Alessandrini et al. 2015; Pernestål Brenden and Kottenhof 2018), and is tested in the first pilots on public streets in Europe (Alessandrini et al. 2014). OECD International Transport Forum (2015) show in their simulations that the concept of utilizing high capacity public transport together with DT/SDT services is promising from a sustainability perspective. To further investigate this concept would be interesting for future research. This research would benefit from including also multi-modal trips.

Most of the simulation studies cover larger urban areas or city centres. However, VKT by car is to a large extent undertaken between cities, within smaller cities, in rural areas and from rural areas into city centres. It would be interesting to study more applications in these areas, especially as there is a tendency for region enlargement and since the complexity of the traffic environment in city centres with pedestrians and cyclists may to lead to earlier introduction of driverless vehicles in rural areas and on highways connecting cities.

This review shows that understanding the impact driverless vehicles will have on travel demand is a key to understanding the effects of driverless vehicles on VKT and congestion. Meyer et al. (2017) show that the expected increases in travel demand may very well offset the expected capacity increases. There are several reasons to believe that driverless vehicles will increase demand for travel: First, as time spent in the car can be used to other tasks than driving travellers are likely travel more. Second, travellers might relocate to live in places that require longer travel distances. Third, new user groups previously not allowed to drive may use the new services. Some research on travel demand has been presented. Truong et al. (2017) estimate increased demand for new types of services due to new user groups (elderly and young people). Krueger, Rashidi and Rose (2016) show in a stated preference survey that the adoption rate may be different in different user groups. Modelling travel behaviour is however difficult at this stage, since driverless vehicle mobility concepts do not exist yet as a mode choice for the travellers, and data is therefore lacking. One way to tackle the lack of data is to use sensitivity analysis to study how the simulation outputs are affected by increased travel demand. In addition to lack of data, a challenge in these types of simulation studies is the baseline for comparison. Should the baseline be today's transport system or a do-nothing scenario for the future?

The reviewed papers show that VKT will increase, except for some cases of high shares of SDT services. This is an effect that is further enhanced by the expected increase in travel demand. As touched upon in some of the reviewed papers, this will probably affect traffic flow and congestion. Traffic flow and congestion are central parameters for travel time and level of service, but also for urban planning and for policy-makers. Therefore, more detailed investigations of these effects would be interesting.

Some of the reviewed papers simulate the competition between DT and SDT services (Hörl 2017), and between DT/SDT services and public transport (Chen and Kockelman 2016; Childress et al. 2015; Davidson and Spinoulas 2016; Hörl 2017). However, none of the reviewed papers simulates more than one operator for the same mobility concept. This corresponds to the situation where there is only one operator that has a monopoly. But what happens if there are several operators and thus competing fleets of driverless taxis? Also, the service offer is in the simulations assumed to be similar in the whole area and trips crossing the boundaries of the simulation area are excluded or truncated. This calls for research on more complex mobility concepts and service offers.

Conclusions

Twenty peer-reviewed papers that present simulation studies on the effects of driverless vehicles have been reviewed and analysed to show what applications have been studied up to now in the literature and to provide an overview of the effects these studies report. Furthermore, areas for future research needed to get a comprehensive understanding of the effects of driverless vehicles have been identified.

In the reviewed papers, the scale of application spans from a single bus line to a whole country, with a clear bias towards larger cities and city centres. The reviewed papers cover five different mobility concepts, including private automated vehicles, automated taxi services, and automated bus services, with a clear bias towards automated taxi services. Penetration rates spans from 2% to 100%.

There are four aspects of effects of driverless vehicles that were considered in a majority of the reviewed papers: trip cost, VKT, fleet size, and waiting time. Among those, trip cost (DT: 0.5 €/km, SDT: 0.25 €/km), fleet size (1 CDC = 12 DT, 1 CDC = 16 SDT), and the waiting times (~5 minutes) show only small variations across the reviewed papers. VKT, on the other hand, show large variations between the papers (e.g. -34% to +195% for DT). VKT is to a large extent dependent on the assumptions made, e.g. trip cost and VOT. At the same time, these parameters are to estimate or predict due to the limited experience of real applications.

This review shows that the effects of driverless vehicles are unevenly distributed from a spatial perspective. There will be more vehicles, more parking demand, shorter waiting times for DT services, and more traffic in the city centres than in the suburbs. This also leads to more congestion and decreased accessibility to the city centres, while congestion will decrease on highways.

Furthermore, this review shows that ride sharing (in SDT services) has a potential to reduce VKT, and thereby energy consumption and congestion, if the level of sharing is sufficiently high. However, a lower trip cost due to sharing does not seem to be sufficient to attract travellers to ride sharing. To achieve sufficient levels of ride sharing that lead to VKT reductions other incentives or policy regulations are needed.

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