1. INTRODUCTION

During the 93rd Annual Meeting of the Transportation Research Board in 2014, there was a workshop dedicated to the activity-travel behavioral impacts and travel demand modeling implications of driverless cars. In this context, one of the presenters deemed shared autonomous vehicles as the “new transit system”. While this assertion was not shared by all participants, it immediately brought to one of the author’s mind the famous claim by Robert Moses in 1948: “Today we are well underway to a solution of the traffic problem” when claiming that building more highways, bridges and lanes instead of providing public transport was the key to solve the major transportation issues affecting urban areas.

Autonomous vehicles (AV) do indeed offer several opportunities that can and should be – wisely implemented – incorporated into future transport systems. Nevertheless, all these opportunities also carry some risks that have the potential to attenuate or eliminate the benefits associated with this technology. Hence, it should not be surprising that this paper starts similar to Smith (2012), who was one of the first warning voices remarking that the hopes set on autonomous vehicles, sensors and computers to solve traffic problems resemble notoriously the hopes set on car use and infrastructure in the 1960s (also see Meyer et al., 2017). Against this background, the objective of this paper is to present a literature-based systemic analysis of different opportunities and challenges that are associated with autonomous vehicles taking over the road, highlighting different strategies that can be implemented by responsible authorities in order to steer the development of transport systems towards sustainability. While previous works have aimed at providing an overarching structure for the causal chains and resulting effects that autonomous driving might have on travel on the base of System Dynamics (Kuhnimhof 2015, Gruel and Stanford, 2016), the paper at hand presents an economic conceptual exploration of the first- and second-order effects[1] of autonomous vehicles based on well-established concepts of the transportation economics literature.

First and foremost, it is important to clarify that this paper deals with fully automated vehicles, i.e. automobiles that are capable to perform all driving tasks and no driver is required during the entire journey (level 5 of automation according to SAE, 2014). Furthermore, the focus is set on passenger transport and any possible implication associated with automated freight transport is not taken into account. This work deals mostly with motorized transport (although without losing sight of non-motorized passenger transportation), subdividing it into private and public transport. Private transport includes traveling with privately owned automated vehicles (referred to as automated cars) as well as with autonomous car sharing systems (referred to as ACS or automated taxis). The latter, together with autonomous ride sharing (ARS), are defined as shared autonomous vehicles (SAV); in contrast to ACS, ARS defines a system where several parties are allowed inside the autonomous vehicle at the same time. Such system is considered to be an integral part of future public transport (PT) systems. Overall, fully automated vehicles are in this paper assumed to operate in all forms of motorized transport, i.e. as private vehicles, in sharing systems, and in PT systems. Finally, we limit our analysis to the

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[1] For the purposes of this paper, changes in the transportation systems associated with the introduction of AVs are categorized in first- and second-order effects. The former relates to changes that can be directly ascribed to the introduction of the technology (e.g. improvements in driving efficiency), while the latter stand for developments that are due to changes in transport demand (these effects are also known as rebound effects).

transportation system, leaving considerations associated with the labor market aside (e.g. eventual job losses associated with the automatization of vehicles are not being considered or likewise it is assumed that, in the long term they do not have major effects due to reconversion of the labor force).

Finally, the paper concentrates on short and medium term effects of autonomous vehicles. This essentially means that changes in land use structure and changes in supply channels for resources and human capital are not considered, as these developments will depend on how authorities tackle the aforementioned short and medium term effects of autonomous vehicles.

The remainder of the paper is organized as follows: Section 2 summarizes the first-order effects of autonomous vehicles discussed in the literature. Section 3 offers a structured overview and discussion of the main possible systemic effects of autonomous vehicles. Section 4 presents different policy aspects and discusses strategies in order to enable decision makers to shape transportation systems for the introduction of autonomous vehicles in the future. Finally, Section 5 summarizes the main findings of the paper.

2. FIRST-ORDER EFFECTS

Over the past few years, first-order effects (understood as direct technology effects on the transportation systems and not considering travel behavioral adaptations) of autonomous vehicles on transportation systems have been extensively discussed in the literature. Several studies offer a detailed description of the potential benefits associated with the introduction of this new technology (e.g. Thomopoulos and Givoni, 2014; Fagnant and Kockelman, 2015; e-mobil BW GmbH, 2015, among many others).

For example, it is expected that autonomous vehicles will lead to a reduction in the generalized costs (understood as the monetarized sum of all costs experienced by the users, such as fare, travel time, waiting time, etc.) of taxi systems and private cars. For both these forms of private transport, the reduction is on the one hand related to cost-efficient driving, i.e. the fuel efficiency gains that (connected) driverless vehicles will offer. Without the necessity of a qualified driver on board on the other hand (Litman, 2014; Lenz and Fraedrich, 2015), taxi systems will become ACS systems, and user prices might drop with operational costs (Bösch et al., 2017a). The latter effect is not as relevant for autonomous private cars; still, they would be able to drive to their parking position without human interaction, so passengers can enter/exit the vehicle directly at the origin/destination of their trips (Fraedrich et al., 2015). Presumably, this yields a significant reduction in the generalized costs of parking, in terms of both parking fees and searching time (Litman, 2014; Correia and v. Arem, 2016), as after dropping the passenger AVs may undertake the search for a cheaper/free parking place on its own (eventually driving back home or even remaining on the traffic for short stays) . Both possible developments (cost-efficient driving and reduced generalized parking costs) would in consequence imply a reduction of the generalized costs of travel for private vehicles.

Opportunities for public transport systems related to the introduction of (connected) driverless vehicles are also multifold. In addition to the cost reduction associated with the reduction of personnel costs, with cost-efficient driving or with intelligent prioritization techniques, it is conceivable that PT services are operated in a more flexible and personalized way. Hence, it may be possible to reduce the vehicle size, and to increase the frequency and the density of the network. This would allow combining mass transportation modes (trains, buses) with fixed route plans in high-demand areas with flexible smaller vehicles for last mile trips (Lenz and Fraedrich, 2015; Yap et al., 2016), overall increasing the attractiveness of public transportation by reducing the generalized costs. Finally, ARS systems, where trips of passengers are pooled and user-costs are split between the different parties might come into place.

Furthermore, many studies associate autonomous vehicles with improvements in traffic flow and increases in road capacity, which are likely to affect both, private and public transport (Tampere et al., 2009; Shladover et al., 2012; Litman, 2014; Friedrich, 2015, among others).[2] These improvements are related to the implementation of adaptive cruise control (ACC; Kesting et al., 2007) or cooperative adaptive cruise control (CACC; Piao and McDonald, 2008; Schakel and v. Arem, 2010) as well as intersection control systems (e.g. Reservation Based Intersection Control, RBIC; Dresner and Stone, 2005; Le Vine et al., 2016). In this context, some authors argue that significant improvements can only be expected once a certain critical amount of autonomous vehicles has been reached (Shladover et al., 2012; Bierstedt, 2014). Kestin et al. (2005), in contrast, claim that even small proportions of autonomous vehicles would lead to a significant increase in the maximum flow on the roads. Many authors then argue, that this greater capacity will, in consequence, result in less traffic congestion and shorter travel times (Litman, 2014; Pinjari et al., 2013; Heinrichs and Cyganski; 2015). Similarly, Fagnant and Kockelman (2015) postulate that high shares of autonomous vehicles would lead to an increase in the reliability of travel time. In any case, as a first-order effect, travel time and reliability gains are to be expected, which in turn, implies a reduction of the generalized costs of travel.

Apart from benefits in the transport system, autonomous vehicles are often associated with a reduction in negative environmental externalities[3], namely global and local exhaust emissions and traffic safety:

1. Energy-efficient driving through automation has, amongst others, been discussed by Bullis (2011), Fagnant and Kockelman (2015), and Gruel and Stanford (2016). These improvements are expected to be achieved by a homogenization of traffic flows (e.g. platooning), which essentially tries to avoid unnecessary acceleration and deceleration (Klaußner and Irtenkauf, 2013; e-mobil BW GmbH, 2015). This could lead to a reduction of specific (i.e. per vehicle kilometer traveled – VKT) fuel consumption and therefore emissions. Apart from reducing the environmental externality, this effect also leads to a direct benefit through cost-efficient driving as discussed above.
2. Improved road safety by eventually eliminating human risk factors has, amongst others, been discussed by Fagnant and Kockelman (2015) and e-mobil BW GmbH (2015). According to Statistisches Bundesamt (2015), roughly 90% of traffic

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[2] Actually, improvements in traffic flow do not yield an increase in physical road capacity, but rather a decrease in the capacity utilization. For simplification, and since both effects lead to an efficiency increase, we use the term `capacity increase´.

[3] Because of the limited impacts of autonomous vehicles on noise levels and damages, we do not discuss this externality further. However, benefits of AVs in this context are conceivable if the vehicles are bundled together and therefore overall emit less noise emissions than when driving alone one after the other. To the knowledge of the authors, there is as of now no contribution in the literature that investigated this potential.

accidents in Germany are caused by human errors. These values are in line with the results reported by the National Highway Traffic Safety Administration (2008) for the US. Fagnant and Kockelman (2015) expect that road accidents will be reduced by 50% already at a market penetration rate of autonomous vehicles of only 10%. With a market penetration rate of 90%, they estimate a decrease of traffic accidents by 90%. Other studies indicate that, as long as vehicles are not fully automated, accident risk might increase since drivers adjust their behavior and, in consequence, fail to adequately and quickly react to emergency situations (see Mahr and Müller, 2011, for an example with ACC systems). Moreover it is likely that the lack of human interaction (e.g. intangible codes, eye contacts, among others) also creates risk situations. In the long run, however, it is likely that specific accident risk will be reduced by the introduction of autonomous vehicles.

Other benefits associated with autonomous vehicles are related to the mobilization new user groups such as elderly, mobility impaired people or children, as well as to the independent car use of travelers without a valid driver's license. A (higher) participation of these user groups in economic and social life might yield positive externalities as the 3-9% increase in VKT suggests which has recently been estimated for Germany and the US by Kröger et al. (2016); in the Netherlands, an increase of 4%-26% in VKT could be expected in association with autonomous vehicles (Milakis et al., 2016). Moreover, it would also be possible to undertake certain trips by private car that are currently being undertaken by alternative transport modes due to other restrictions, such as trips to and from activities where alcohol is consumed or overnight trips.

Finally, several studies have addressed potential changes in the valuation of time spent in the vehicle as autonomous vehicles will offer many possibilities to reduce the disutility of travel time, by relieving the user of the driving tasks and allowing to dedicate the time in the vehicles to activities, deemed as more meaningful by the driver (Silberg et al., 2012; Heinrichs, 2015; Zmund et al., 2016). For instance, a study conducted by Willumsen and Kohli (2016) showed that most transportation experts expect a significant reductions on the subjective value of travel time savings (SVTTS). That is, travel time will most likely be perceived less negatively than today.

Overall, by looking at the direct effects of autonomous vehicles, it can be stated that most studies mainly see positive effects for society: other things being constant, negative environmental externalities will be reduced, access, egress as well as in-vehicle times will decrease, and opportunities for more flexible and personalized means of transport will emerge. Additionally, the mobilization of mobility impaired people and the independent car use of travelers without driver's license is expected to provide benefits. Unfortunately, only estimating the benefits of the direct effects is unlikely to show the full picture of consequences that will emerge once autonomous vehicles enter the roads (Kuhnimhof, 2015). As we will present in the next section, many of the discussed impacts might – without adequate policy interventions – not materialize when systemic effects are considered; an obvious example is the expected change in mode-choice behavior, with all its consequences, induced by the reduction in the generalized costs of private road transport.

3. SECOND-ORDER EFFECTS

As briefly summarized in the previous section, direct effects of autonomous vehicles have been thoroughly considered in numerous publications. Nevertheless, these effects are normally addressed independently and second-order effects, i.e. developments that are due to shifts in the demand for transportation, are often neglected. In this sense, it is be possible that first-order effects appear in strengthened or weakened form or even not at all, when interactions between them are considered. It could be expected, for instance, that the aforementioned capacity improvements or the reduction of fuel consumption and emissions have a smaller impact than expected, when taking into consideration that autonomous vehicles will not only have to interact with non-autonomous vehicles (mixed traffic), but also with pedestrians, cyclists, vehicles parking in second row, trucks loading/unloading, etc.

Along these lines, it is possible to identify several systemic (or second-order) effects, which go beyond the first-order impacts of autonomous vehicles, as they are the results of changes in travel behavior given the aforementioned first-order effect. Special emphasis should hereby be put on possible shifts between the demand for motorized private and public transport, as this may outweigh the direct effects of transportation policies and processes (Thomson, 1972). Figure 1 provides a systematic (however non-exhaustive) representation of potential consequences associated with the introduction of level 5 autonomous vehicles. This scheme offers a rather functional representation of first- and second-order effects and does not aim for an analysis based on System Dynamic (Gruel and Stanford, 2016). Rather, we conduct an economic analysis establishing connection between first- and second-order effects on the basis of well-established concepts and cause-and-effect chains in the transportation economics literature. In this figure, solid arrows indicate a positive directional correlation while dashed arrows represent a negative directional correlation. As this section is centered on the systemic effects of automation, here we consider only variables expected to exhibit significant systemic effects (and for this reason ignoring e.g. safety or noise issues, as no significant travel behavioral changes and demand shifts can be expected in associated with them). For illustrative purposes, we in a first step assume (i) that riding an autonomous vehicle has no effect on the subjective value of travel time savings (SVTTS), and (ii) that the overall transport demand in terms of total trips for motorized alternatives remains constant with fixed destination choice (demand shift between alternatives is allowed though); these two assumptions will be relaxed at the end of this section. Further, it is assumed that the responsible authorities do not implement any congestion pricing in order to force users to internalize transport-related externalities or any restrictions associated with empty-vehicle trips (so-called zero-occupant or ghost-trips, including empty parking trips and relocation trips; we will relax this assumption in Section 4). Finally, it is also assumed that taxis and public transport would no longer require a driver, i.e. the road-based part of these modes has transformed into more or less flexible SAV systems.

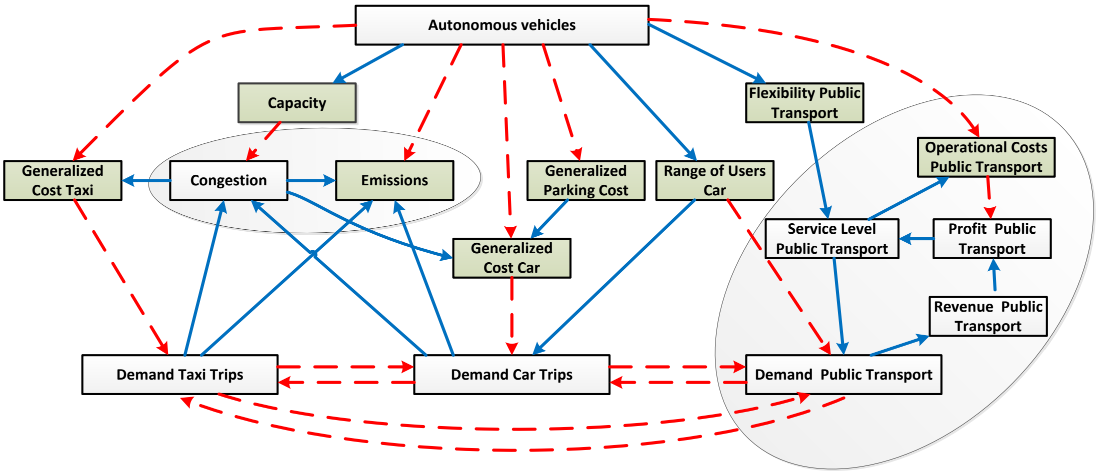

Figure 1 – Potential first-order and second-order effects related to the introduction of autonomous vehicles. Solid arrows indicate a positive directional correlation; dashed arrows represent a negative directional correlation.

Looking at the green-shaded boxes in Figure 1, it is possible to identify the direct effects of autonomous vehicles discussed in Section 2, namely:

1. the reduction in the generalized cost of taxi operation and usage (no drivers, cost-efficient driving) and cars (cost-efficient driving, lower generalized parking costs),
2. the reduction in operational costs of public transport systems (no driver, cost-efficient driving),
3. the opportunities associated with a more flexible design of public transport services,
4. the increase in the flow capacity of roadways and the resulting reduction of congestion levels,
5. the reduction of air pollutant emissions (efficient driving), and
6. the increase in the number of car users.

For the systemic analysis, it is important to consider that all the aforementioned effects would shift demand between the different travel alternatives: lower generalized costs for taxi and car trips, for example, would increase the demand for these transport modes. Additionally, new automobile user groups (e.g. impaired people or children) would further increase the demand for private car while reducing the demand for public transportation, as these users would no longer be PT captives.

On the lower right corner (denoted by an oval) is the so-called vicious or virtuous circle of public transport (VCPT; Ortúzar and Willumsen, 2011). In the positive case, better supply (e.g. higher flexibility of public transport) would result in greater PT demand, which, in turn, increases the revenue of the public transport system; a positive balance between revenue and costs eventually allow for improving the level of service[4] etc. In the negative

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[4] Here, the actual fare paid by the users is considered to be part of the level of service, and it is assumed that a wider coverage, higher frequency, lower fare and shorter travel, waiting and walking times characterize a higher level of service, and vice versa.

case, lower demand levels (e.g. because of a shift towards motorized private transport) would result in lesser revenues and system losses and in the longer run in a poorer level of service, again dampening the demand for PT, etc.[5] In first-order, autonomous vehicles would have a positive effect on the VCPT as they would reduce operational costs for the transport provider, while the associated higher flexibility would allow providing a better service. In contrast, the potential reduction in demand for transit systems could have the opposite effect, yielding a negative effect on the VCPT. The overall effect on the VCPT therefore depends on how these two effects (higher attractiveness because of cost-efficiency and flexible supply vs less attractiveness because of lower supply/demand levels) balance in the long run. Furthermore, one of the main justifications for subsidizing public transport refers to its positive externalities as an inclusive mobility alternative; while these externalities are not expected to disappear, their impact may be reduced, as competing alternatives become more inclusive (lower price and absence of driver).[6]

Overall, the above shows that changes in the modal split have the potential to cause significant rebound effects in the system. As we have, initially, assumed that the overall transport demand for motorized alternatives remains constant, any increase in the demand for a given transport mode would necessarily reduce the demand for the remaining alternatives. In this sense, if private transportation alternatives (taxi and private automobiles) experience a higher demand, it must result in a lower demand for public transport. This, in consequence, would lead to higher traffic volumes on the roads, and thus, to more congestion and air pollutant emissions. Here, it must be noted that the effect on emissions may be dual in nature: first, absolute emissions would increase as several trips are undertaken by less environmentally friendly modes; second, greater congestion levels would extend the duration of the trips and increase stop and go traffic situations, which is both associated with higher specific (i.e. per VKT) emissions.

The balance between autonomous taxi (or ACS) trips and private car trips clearly depends (among other attributes) on the difference in generalized costs. Today, car sharing is for many use cases considered to be too expensive and access efforts are relatively high. Through ACS systems, car sharing would become cheaper and more accessible (through a much more efficient operation of the fleet) and new business models could emerge, eventually even influencing the car ownership rate in the population. However, it should be pointed out that even in such situation and even if the overall transport demand for private transportation in terms of total trips with fixed destination choice would remain constant, this does not mean that the total number of VKT also remains constant; in fact, an increase is to be expected: This increase could arise (i) because splitting of joint trips with pick-up and drop-off purposes is facilitated (e.g. driving directly to work in two separate cars, overall reducing individual travel time and the passenger load factor), and (ii) because of ghost-trips with the purpose of relocation (especially in the case of ACS and ARS systems,

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[5] It should be noted that higher operating costs per person not necessarily influence the level of service, as the responsible authority may decide to increase subsidies in order to guarantee a certain level of service to avoid the VCTP and a collapse of the transport system as a whole. However, maintaining a certain level of service for lower demand levels requires more public funding per PKT, increasing the pressure on the authorities; subsidizing the transit system, however, remains as a key tool of the authorities to steer transportation and urban systems (see Section 4).

[6] Nevertheless subsidizing public transport would still be economically justified in the absence of such positive externalities, as long as the regulatory authorities do not include pigouvian taxes on the externalities caused by private transportation. Under these circumstances subsidizing the alternative associated with the lesser externalities can be considered as a second-best to maximize social welfare.

but also in the case of private cars, when shared by various members of the household) and parking. The latter relates to the possible development that vehicles will not necessarily be parked near the travel destination, but where it makes economically sense for the user (Chapin et al. 2016). It is even possible, that vehicles be sent back home for parking or simply circulate around the block for activities with short durations.

This possible increase in VKT through the introduction of autonomous vehicles has already been estimated/projected in several simulation experiments, e.g. by ITF (2015), Levin et al. (2016), Maciejewski and Bischoff (2016), or Fagnant and Kockelman, 2016). In these studies, the current demand for private car trips is entirely replaced by SAVs (ACS and ARS); such situation essentially postulates a state where owning a private car is either forbidden or the SAV systems are constantly available and by far cheaper than private car use, so that nobody would use their car for inner-urban trips. The authors observe an increase in vehicle kilometers traveled and in the mean travel time in comparison with the base situation. The magnitude of the increase is, however, highly dependent on the desired level of service i.e. the number of SAVs considered to satisfy a given demand (the more SAVs, the shorter the waiting times before a passenger is picked up; Levin et al., 2016; Maciejewski and Bischoff, 2016; Fagnant and Kockelman, 2016) . The main driving force behind this phenomenon is that the effects of additional relocation ghost-trips on congestion levels are larger than capacity gains resulting from efficient driving. In reality, however, the situation could be significantly worse, as these studies did neither consider ghost-trips with the purpose of parking nor any shifts in demand towards motorized private transport. For a dynamic equilibrium model, van den Berg and Verhoef (2016) find that even though road capacity increases with the share of AVs, switching to an autonomous car can yield negative externalities because of increased congestion costs resulting from changes in departure time behavior. By considering changes in transport demand (based on simple assumptions), Bösch et al. (2017b) suggest that existing transport systems might be a better alternative than introducing an SAV-based service.

Considering the existing literature on capacity improvements, these results are little surprising. As initially postulated by Downs (1962) and Thomson (1972), capacity improvements for private transportation may have a negative impact on the average travel time in a system (Downs-Thomson paradox). It has been validated empirically in various studies (Cairns et al., 1998; Cairns et al., 2002; Goodwin and Nolan, 2003; Duranton and Turner; 2011). Even though the occurrence of the paradox has been demonstrated for infrastructure capacity improvements, there is no reason to expect that it cannot arise for capacity improvements resulting from efficient driving, as the phenomenon was (mathematically) derived for capacity improvements in general. The reasons behind this phenomenon are also well known: under normal circumstances, the introduction of new technologies and alternatives should lead to an increase in social welfare, as gains and losses are balanced by the users. This, however, does not necessarily apply in the presence of negative externalities. As these effects are not internalized by the users, they must be absorbed by the entire of society (if no regulation to internalize them is introduced) and, as a result, the complete system may end up in a worse-off situation. In the case of the Downs-Thompson paradox, capacity improvements initially favor smaller, less efficient vehicles (with higher externalities per passenger-kilometer), leading to a modal shift towards them. If the externalities associated with this modal shift exceed the original capacity improvements, the travel time deteriorates and the phenomenon arises.

A similar phenomenon related to the automation of public transport might be the replacement of big buses by smaller vehicles offering a more flexible and personalized service, which in consequence results in an increase in the capacity utilization of the network. This may lead to social losses in a similar fashion as the Downs-Thompson paradox: smaller, less efficient vehicles (in terms of externalities per passenger-kilometer) with higher frequency and more flexible itineraries have the potential to reduce users' generalized private costs, leading therefore to demand shifts at expenses of the demand for more efficient larger vehicles increasing the negative externalities in the system. As in the Downs-Thompson paradox, if these externalities exceed the gains associated the new alternative, it would lead to a welfare loss. While at first sight, this phenomenon seems to have a potential less important effect than modal shifts from public to private transportation, both phenomena may add up, overall increasing congestion levels.

In the context of Figure 1, these externalities are represented by congestion and emissions and denoted by the central oval[7], and they play an important role when evaluating the impacts of AVs. Whether transportation systems will improve or deteriorate without further policy interventions depends on how the levels of positive first-order and systemic effects (which include improvements in accessibility among other wider economic benefits) and potentially negative systemic effects (associated with demand shifts) balance: In rural areas and in under-congested small cities, it is possible that the negative systemic effects be low in magnitude; hence, automated vehicles would be expected to lead to an increase in social welfare. Contrariwise, in highly congested larger cities, the negative externalities may exceed the benefits, leading to a loss of social welfare (Thomopoulos and Givoni, 2014).

Before discussing possible management options to avoid welfare losses resulting from the introduction of AVs, the following two paragraphs now present the potential implications of relaxing the initial assumptions regarding the unchanged valuation of travel time and the constant demand for transport, respectively.

Relaxing the assumption of unchanged valuation of travel time

So far we have assumed that the SVTTS remains constant. This assumption, however, does not seem plausible, since, as previously mentioned, autonomous vehicles should increase the range of activities that can be performed during a trip, diminishing thus the SVTTS (Zmund et al., 2016; Willumsen and Kohli, 2016). In this context, it should not be expected that changes in the SVTTS affect all alternatives equally. In the case of public transport, little or no changes are to be expected, as individuals would still share the space with other passengers and they will not be affected by changes in the control of the vehicle. Major changes, however, can be expected in private transportation; while, in the case of autonomous cars, an improvement can be achieved by making possible for the user to dedicate their travel time to alternative meaningful activities, increasing privacy can be seen as the main improvement (regarding the SVTTS) of autonomous taxis in comparison with current taxi services. In principle, a similar SVTTS can be expected for autonomous cars and autonomous taxis, although the potential of private cars seems to be a little larger,

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[7] It is important to note that other externalities associated with autonomous driving, such as improvements in traffic safety or the inclusion of impaired persons are not being considered in this analysis, because their systemic effect are of low magnitude (i.e. they do not cause significant demand shifts). Considering these externalities would improve the benefits of autonomous vehicles.

as they offer the owner a wider scope for design. It must, however, be pointed out here that the reassessment of the SVTTS will not affect all individuals and professional groups equally, as different interests and occupations would be associated with widely different ranges of potential alternative uses for the time spent in the vehicle.

Ceteris paribus, a decrease in the negative perception of travel time (i.e. SVTTS) would further diminish the generalized costs of private transportation, leading to higher demand for these alternatives and thus to more congestion (Smith, 2012). As a result of the latter, the generalized costs would increase. This implies longer driving times, which is perceived less negatively. Therefore, the systemic impact depends on the magnitude of the benefit induced by the lower valuation of time compared to the magnitude of the loss owed to higher travel times. This would also influence the impact on public transport: even though no significant changes in the SVTTS are expected here, the VCPT could be triggered and put public transport under pressure as demand drops because of a modal shift towards private transportation and the level of service of public transport deteriorates if sharing congested facilities with private transport. As a consequence, a new appraisal of the SVTTS would cause a reduction of the generalized costs of autonomous cars and autonomous taxis. Hence, it would add up with the first-order effects of autonomous vehicles described in the previous section, intensifying the systemic effects depicted in Figure 1.

Relaxing the assumption of a constant demand for motorized transport

So far, we assumed that the overall demand for motorized transportation would remain constant in terms of total trips, and that destination choice is also fixed. In the light of the previous discussion, this assumption appears unlikely to hold. Basically, demand for motorized transportation will go up if the private generalized costs of motorized transport go down and vice versa. This implies that lower generalized private cost might lead to induced demand through increased accessibility (Goodwin, 1996; Weis and Axhausen, 2013; Meyer et al., 2017) in the following forms[8]:

i) Increasing the attractiveness of traveling in general (trip generation)
ii) Causing a shift from non-motorized to motorized alternatives (modal choice)
iii) Extending trip distances (destination choice)

It is, however, unclear whether private generalized costs would go down, as congestion is likely to increase the privately experienced costs. Notwithstanding, it can be expected that private generalized costs be lower than social costs, as (in the absence of regulatory policies) individuals do not internalize the external effects of their travel behavior. While it is possible to think of some positive externalities associated with an expanding demand for motorized autonomous alternatives, such as the mobilization of impaired and elderly people, negative externalities, such as congestion, air pollutant emissions, lesser health benefits (due to the shift from non-motorized to motorized alternatives) or spatial segregation (due to the longer trip distances) appear to be farther-reaching[9]. Under these

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[8] Weis and Axhausen (2009) showed, on the basis of empirical results that both trip generation and destination choice exhibit a inelastic positive accessibility elasticity and an elastic negative price elasticity.

[9] In the case of increased demand for motorized transport, it is not possible to establish a-priori the direction of safety effects, as more and longer motorized trips should increase the number of accidents, while the shift from non-motorized alternatives to autonomous vehicles may have a positive effect.

circumstances it is unlikely that a larger demand for motorized transport would lead to improvements in social welfare. Such a situation can only be expected in sparsely populated areas, where mobility effects (including wider economic benefits) might outweigh negative externalities. The opposite effect, i.e. a hypothetical reduction in the demand for motorized transportation, would only be possible if the private generalized costs of motorized transportation increase. Assuming decreasing generalized costs due to automatization, this is only possible in a hypothetical scenario, in which congestion (despite lesser demand) increases above the reductions in the generalized costs. An increase in congestion despite lesser demand is, in turn, only possible due to the existence of ghost trips. Such a scenario would result in large losses in social welfare.

Correia and v. Arem (2016) consider demand shifts and the SVTTS in a simulation (relying on strong assumptions in this regard). The effect is a further increase of private transportation. The simulation likewise suggests that this increase does not lead to major congestion problems, which can be tracked down to the characteristics of the street network, initial congestion levels and size of the urban area under consideration (Delft in the Netherlands). To summarize, several indicators suggest that relaxing the two initial assumptions on the unchanged valuation of travel time and the constant demand for transport will further increase the negative externalities of additional private transport demand. It therefore seems necessary to develop policies that can help to prepare our cities for the challenges related to the introduction of autonomous vehicles. This will require putting up a regulatory framework to allow the positive effects to unfold without the negative impacts to dominate.

4. POLICY ASPECTS

As discussed in the previous section, autonomous vehicles have the potential to facilitate the use of private transportation, and thus – mainly in highly congested urban areas – might exacerbate negative externalities. Additionally, they carry the risk of triggering a vicious circle which eventually yields the decline of public mass transportation. Against this background, this section discusses regulatory options for transportation systems in cases where externalities are expected to reach a relevant magnitude. This important dimension for policy setting has mainly been ignored in the transport economic literature (notable exceptions, though not providing an in-depth discussion on the topic, are Smith et al., 2012, Zmund et al., 2016, and Bösch et al., 2017b). Other literature has instead set the focus on regulations regarding technical aspects, such as vehicle standards, liability and privacy issues and investment attraction (Fagnant and Kockelman, 2015; Anderson et al., 2016). This section therefore aims at providing an overview of additional aspects that will become important for sustainable transportation planning.

In terms of policy setting, it needs to be emphasized that the effectiveness of indirect management alternatives that are currently in place in many cities would severely be reduced after the introduction of AVs. For instance, parking fees and parking restrictions, often discussed as a substitute to city tolls, could lose their steering effect as parking would no longer be associated with the travel destination, e.g. through valet-parking (i.e. the vehicle drops the users at the destination and undertakes the parking maneuver automatically; Heinrichs and Cyganski, 2015).

Providing high quality public transport supply is typically seen as another effective management strategy. However, declining costs in private transportation could reduce the price-gap between private and public transport, making it more and more difficult to compensate for typical negative features of public transport, such as transfers, scheduling, lack of privacy, etc. Thus, scenarios where autonomous vehicles lead to more intermodality (especially last-mile intermodality) are unlikely as empirical evidence shows that strong negative impacts arising from transfers and scheduling issues (Train, 1979; Frank et al., 2008; Bahamonde-Birke, 2016; among many others) are hardly compensated in the context of diminishing generalized cost differences. Favoring public transport by reducing user prices in this situation might come to mind as a policy option in order to counter the reducing price gap (Bösch et al., 2017b). Analytical and simulation-based studies, however, show that in many situations the system-optimal user price of public transport is already close to zero as long as the private transportation mode is not regulated in an efficient way by internalizing their negative externalities through tolls (see, e.g., Tirachini and Hensher, 2011; Kaddoura et al., 2015). Negative user prices for public transport cannot realistically be considered as an option as they would yield unreasonable levels of induced demand, much higher than those already experienced today where the cost of mobility is generally too low. Hence, since price reductions do not seem feasible, one policy option to mitigate the negative effects of autonomous vehicles on society is to ensure high quality public transport by increasing frequency, reducing travel time and generalized travel expenses (in order to compensate the reducing price gap) and thus avoiding the VCPT and the collapse of the urban transport system. This might imply expanding financial resources for subsidizing public transport even more than today because these subsidies are mainly justified by the subsequent avoidance of negative externalities from private transportation.

Another alternative to regulate autonomous vehicles would be to impose the restriction that a person in possession of a valid driver’s license must always sit on board (as currently in the US states of Florida and Nevada; Anderson et al., 2016). However, such a regulation appears to be excessively restrictive, and rules out many advantages of the technology. This concerns in particular the inclusion of mobility-impaired people. Relaxing this restriction may result in a ban of ghost-trips or its limitation to a given radius for parking purposes (Lenz and Fraedrich, 2015). While such restrictions would indeed enable the technology for impaired people, they would still prevent some key advantages of driverless vehicles to materialize, such as the use of autonomous taxis, car sharing (public and private – e.g. a vehicle is shared by different members of a household) and autonomous valet-parking (only the ban of ghost-trips).

In general, implementing such limitations seems to be associated with great difficulties and costs, and may create incentives for bypassing the law. In addition, they are not an effective mechanism to address the negative externalities of (private) transportation (e.g. limiting the search for parking slots to a given radius could result in vehicles cruising around in congested areas where the parking demand locally exceeds the supply) and do not contribute directly to easing traffic problems in hyper-congested areas. These aspects, in conjunction with hampering opportunities of the technology as well as the difficulties associated with the implementation of these restrictions, make them implausible in the long term.

Other alternatives may comprise limiting the access of motorized private transportation to congested areas, establishing a substantial number of PT exclusive-lanes, and enforcing higher car occupancy rates, especially for ARS systems. Overall, this would increase the generalized cost of private transportation and favoring PT as well as indirectly the non-motorized modes. In this context it is important to note that autonomous taxis should not be favored over privately-owned vehicles, as they do not exhibit social benefits (in terms of reduction of negative externalities) to justify such advantages. Nonetheless, factually, prohibiting the car-use in several parts of the city may be considered as overly restrictive and would hamper many of the advantages associated with autonomous vehicles. Additionally, controlling restrictions on car occupancy rates may be associated with significant difficulties. Furthermore, such restrictions would not stop the replacement of larger busses, potentially triggering the aforementioned Downs-Thompson-like paradox associated with the replacement of big busses by smaller flexible vehicles. Finally, replacing parking fees by this kind of restrictions would also forego an important revenue stream.

Therefore, road pricing, often referred to as the most efficient alternative for managing urban transport systems, might in the future experience much more attention in the real world once planners need to design the infrastructure in the presence of autonomous vehicles (Smith, 2012; Bösch et al., 2017b). The basic principles behind optimal (or first-best) pricing in transport are well-known and have been studied extensively (see, e.g., Vickrey, 1969; Arnott et al., 1993; Lindsey and Verhoef, 2001; among many others). Apart from the fact that toll revenues could compensate the losses associated with less parking fees, additional efficiency gains would be achieved through dynamic road pricing which addresses the externalities of transportation directly. Simulation tools for the calculation of first-best tolls in a real-world context accounting for all relevant externalities have recently been developed (see, e.g. Kickhöfer and Kern, 2015; Kaddoura et al., 2016; Agarwal and Kickhöfer, in press). Implementing such first-best road pricing scheme in the presence of autonomous vehicles seems at a first glance quite straightforward: navigation/guidance systems are essential for the functioning of AVs and, hence, could be used for optimal routing and pricing. However, it is likely that there will be a period with both, autonomous and conventional vehicles, on the road (mixed traffic), and such first-best pricing would be difficult to implement for all users. Additionally, optimal pricing would yield price signals that might change at a very fast pace, potentially too fast to be processed by a human being. In such cases, the passenger would not always be able to understand the routing of his or her vehicle and this might lead to confusion. Hence, in the case of mixed traffic conditions, the price system would still need to be understandable for humans in order to unfold the desired steering effect. Finally, several data privacy concerns need to be addressed in future research, and policies need to be developed accordingly.

Toll systems based on either automatic number plate recognition (as in London, Stockholm, Gothenburg or Milan) or electronic tolling (as in Singapore, Santiago de Chile or Dubai) are currently in place in different countries. In this context, one can differentiate two charging systems: the collection of fees for accessing toll zones (e.g. London or Singapore) or a kilometer-based charging system (e.g. Santiago de Chile or Dubai). Both systems, by using toll zones and charging for road use, could have difficulties in the presence of autonomous vehicles. Regarding toll zones, it is questionable whether the system can set powerful incentives not to leave the toll zone, which could lead to more ghost trips (either cruising around or searching for parking slots inside the toll zone) and thus to more congestion and air pollutant emissions. Alternatively, the use of multiple smaller toll zones could also be considered. This might help mitigating these negative incentives (and allow for a tolling closer to the first-best solution) but they cannot be completely eliminated. The problems associated with kilometer-based road pricing are rather of technical-financial nature, as wide toll coverage can be expensive. The sole tolling of the main routes carries the risk of shifting the traffic to the secondary road network. Regarding the control systems there are no major concerns regarding automatic license plate recognition or electronic toll systems. The latter would have the advantage of allowing for variable pricing depending on the current conditions (Goh, 2002); it implies, however, a higher implementation cost. To overcome the aforementioned shortcomings of classic road pricing, hybrid charging systems are conceivable. This way, the regulatory authority may offer to drivers and/or vehicle owners the alternative of allowing for an accurate vehicle tracking in exchange for lower fares. This approach would allow for an accurate pricing system in accordance with the externalities actually caused by the vehicle. Such strategies are also conceivable in order to allow access to high-occupancy vehicle lanes, offering incentives to encourage carpooling, etc.

Regarding the facilitation of shared autonomous vehicle systems by the responsible authority, it needs to be taken into account that ACS systems are more prone to increase traffic volumes than ARS systems. In the latter system, passengers share a car with other parties by bundling trips. For example, Trommer et al. (2016) estimate for urban areas in Germany an *in*crease in traffic volumes (VKT) induced by an ACS system to +5%, and a *de*crease in traffic volume induced by an ARS system to -2%. In consequence, priority should be given to mobility providers that base their business model on shared trips rather than only shared vehicles.

5. CONCLUSIONS

While a large body of literature has highlighted various potential benefits of autonomous vehicles, possible systemic effects, mainly resulting from to-be-expected shifts in demand, have so far mostly been overlooked. Transportation systems are typically characterized by complex interactions between millions of individuals, full of externalities, where first-order oriented policies do not always achieve their goals as negative systemic effects may outweigh the direct benefits of the technologies and policies. That is a lessons learned from the time where policy making concentrated almost entirely on providing infrastructure for individual motorized transport.

In this paper, we therefore analyzed potential systemic effects of driverless vehicles and establish correlations among them on the basis of previous well-established results in the transportation economics literature, in order to provide a systemic overview of the possible consequences of these vehicles entering the roads. We showed that autonomous vehicles may cause significant shifts in the demand for transportation both at the level of trip generation as well as at the level of mode and destination choice, by increasing the attractiveness of travelling and of the motorized alternatives. Under these circumstances, the introduction of autonomous vehicles poses significant risks for the development of transportation systems, especially in relation to a potential advance of the private motorized transport at expenses of non-motorized and public transportation. Such development would be accompanied by an increase of several externalities that many cities are fighting already today, such as congestion or air pollution. This increase in negative externalities is even likely to happen if new business models for on-demand ACS systems reduce car ownership levels in the population as on-road transport volumes are still expected to increase. Hence, the technology has the potential of triggering the vicious circle of public transportation and, without intervention such as city tolls and favoring ARS over ACS systems as supplement to conventional PT, eventually leading to a collapse of the transport system as a whole.

Therefore, it is important that responsible authorities carefully consider the possible systemic impacts of autonomous vehicles since especially current regulatory policies are likely to lose their efficiency (as in the case of parking regulations). In this context, the paper raises awareness that it will be necessary to develop new strategies for steering the transportation systems and guarantee a sustainable transportation planning. Along these lines, we considered several regulatory policies that have been proposed in the past, in the light of their pros and cons. We conclude that implementing tolling systems appear to be the most promising alternative to address the issues arising from the introduction of driverless vehicles. Notwithstanding, tolling systems that are currently in place would have to be adapted in the presence of autonomous vehicles, as they may cause undesirable effects. We therefore strongly suggest that further research be conducted on how to balance the perceived costs of mobility between private and public transportation that will inherently change with the emergence of autonomous vehicles. Certainly, this requires the development of prediction and evaluation metrics that are able to capture changes in mobility behavior as a result of changes in the existence or in the attributes of travel alternatives resulting from autonomous vehicles.

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