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A simulation based assessment of AVs impact on road space in urban areas

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Abstract

It is widely acknowledged that fully autonomous vehicles (AVs) will have a significant impact on mobility. However, we lack a detailed understanding of their effects on traffic operations and space allocation.

This study analyses the impact of AVs on road space. Simulation experiments are run in order to find how much of the road space could be reclaimed for other purposes while complying to certain traffic flux targets. Operationally, this can be described using macro fundamental diagrams (MFDs), which provide the relation between traffic flux and traffic density (and therefore space).

We find that for the same amount of trips, AVs can decrease the road space needed by around 11-12% compared to conventional vehicles (CVs). At the same time, given the existing road infrastructure, AVs potentially triple trips. These findings not only emphasize the effect that AVs will have on mobility, but also give a first insight on how road space allocation to vehicles should be re-evaluated.

1 Introduction and background

Fully autonomous vehicles (AVs) are not yet available to the public and as of today their presence on the road is limited to testing. Nonetheless, it is widely acknowledged that they will have a significant impact on mobility, possibly as soon as in the next decade, when they are expected to hit the market (Maurer *et al.*, 2015). The scientific literature dealing with such possible impacts is already abundant. As the information on how AVs will behave in traffic is limited, such studies are largely based on assumptions or focused on the demand side. That being said, several scientists have hypothesized that thanks to AVs quick reaction times in traffic, once they are widespread, it will be possible to exploit better the infrastructure capacity and, ultimately, reduce or even plainly avoid congestion (e.g. Friedrich, 2015, Fernandes *et al.*, 2012, Guler *et al.*, 2014). This idea has the limitation of not taking into account possible rebound effects, in the form of new demand, which could fill up again the capacity gained. The long term impact remains uncertain (Goodwin and Noland, 2003).

A possible way to look at the problem differently is to set precise goals in terms of total throughput for a road network. A part of the capacity gains would be used to actually increase traffic flux, while the rest could be used for other purposes. Looking at the issue from this perspective has the advantage of making explicit the trade-off between traffic flux and space usage implied by the adoption of AVs.

According to Heinrichs (2015), the future of autonomous mobility is significantly dependent on i) the availability and the integration of connectivity between vehicles, and ii) the acceptance thereof by users. It is clear that the level of vehicle connectivity will have a considerable effect on traffic performance and operations. However for the sake of simplicity, in this paper we concentrate on the conservative scenario, where AVs are privately owned and unconnected to each other.

Some exemplary districts in New York and San Francisco show that the space occupied by roads is between 26% and 35% of the total area (Gonzales, 2011). A brief analysis for the city of Zurich, Switzerland, shows similar values, indicating that a significant amount of space is dedicated to road traffic. With land prices at around CHF 3000 per m^2 in the city of Zurich, we can say that around CHF 900 per m^2 is potentially “lost” to traffic (Moser, 2016). Thus, it is important for city authorities and planners to understand the interaction between traffic and road space allocation. The motivation for this paper is to answer the following questions:

- i What is the influence of AVs on traffic flow in an urban network?
- ii What is the AV’s impact on road space?

We will first introduce a basic methodology for macroscopic traffic analysis in urban networks, and for the computation of the road space consumption of vehicles. Then, we analyse the

changes in road space for a simulation of an abstract grid network. The paper ends with some concluding remarks.

2 Methodology

2.1 MFD estimation

The macroscopic fundamental diagram (MFD) relates average flow and average density of an urban network. We choose the MFD as a performance indicator, since it gives a holistic, macroscopic view of a relatively homogeneous network.

For an urban network we can define the MFD following the outlines of Geroliminis and Daganzo (2008).

$$q_{MFD} = \frac{\sum_i q_i l_i}{\sum_i l_i} \quad k_{MFD} = \frac{\sum_i k_i l_i}{\sum_i l_i} \quad (1)$$

The MFD is based on q_i and k_i , which correspond to the flow and density of link i for time slice t . They are then weighted by the link length l_i . In reality, these values can be estimated through loop detector data, floating car data or a combination of the two (Ambühl and Menendez, 2016).

2.2 Quantifying effects on road space

The road space needed by a vehicle can be defined in different ways. For example, a naive approach would take an aerial photograph and then analyse the space occupied by cars on the photograph. However, this method excludes the temporal factor; hence it does not incorporate the additional space needed for each vehicle to move around. Convent have to keep a certain distance to the next one when driving around. This additional space should be taken into account. Based on Gonzales (2011) we define the *footprint*, r , of a vehicle during its trip as:

$$r = \frac{w t_t}{k} = \frac{w d_t}{q} \quad (2)$$

where w is the lane width, t_t is the duration of a trip and k is the traffic density. We can reformulate the equation when we determine the travel time by dividing the length of a trip, d_t by the speed. We can then replace the multiplication of speed and density with the traffic flow, q . The footprint, r , has units $m^2 h$.

For a network with a constant demand, the average length of a trip, d_t , is constant. With the width of the road constant, we can analyse the change in road space, Δr , needed for conventional vehicles (CVs) and AVs:

$$\Delta r = \left(\frac{1}{q_{AV}} - \frac{1}{q_{CV}} \right) w d_t \quad (3)$$

The footprint of a vehicle is a measure of efficiency and is somewhat counter-intuitive. When comparing the footprints corresponding to different traffic states we need to be careful. For example, in an uncongested network, having a low flow will lead to a higher footprint than a high flow. In other words, the footprint is minimized when the flow is maximized. Any other state of traffic increases the vehicle footprint. Thus, the vehicle footprint indicates how efficiently road space is used. Transport mode A uses road space more efficiently than transport mode B, if A has a lower footprint than B, but can execute the same number of trips.

3 Case study

3.1 Car following model

An important aspect of the simulation is the car following model. For its mesoscopic simulation VISSIM uses a simplified car following model which is based on Mahut (2000):

$$x_{Follower}(t) = \min(x_{Follower}(t - \epsilon) + \epsilon v_{des}, x_{Leader}(t - \tau_{Follower}) - \lambda_{Leader}) \quad (4)$$

with $x_{Follower}$ and x_{Leader} standing for the front end position of the trailing and the preceding vehicle on a link. v_{des} stands for the desired speed of the trailing vehicle, ϵ for the time interval of the meso-simulation step, $\tau_{Follower}$ for the response time of the trailing vehicle, and λ_{Leader} for the effective length of the preceding vehicle, which is the sum of individual vehicle length and the standstill distance. In other words, the following vehicle's position depends on either its desired speed during time interval ϵ , or on its response time and the effective length of the leader vehicle. This model neglects acceleration and braking. However, for the macroscopic view on the effects of AVs it is a simple approach, reducing the computational effort. The following table gives an overview of the values chosen for CVs and AVs. It is based on the assumptions of Friedrich (2015). The vehicle length is assumed to remain the same.

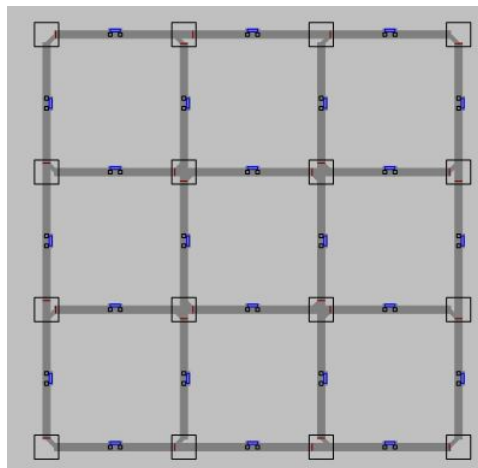
Table 1: Input values for car following model

	CV	AV
v_{des}	50 km/h	50 km/h
τ	2 sec	0.5 sec
standstill distance	1.2 m	0.5 m

3.2 Network and demand properties

The grid network shown in fig. 1 is a 4 by 4 grid with 24 main links, each 120 m long and with two lanes in the same direction. All links are one-way and the direction of travel alternates in parallel corridors. At each intersection, a traffic signal is set to a 60 seconds cycle length, with 27 seconds of green for turning and through traffic, and 3 seconds lost time per phase.

Simulations were run for 1 hour simulation periods during which demand was held constant.

**Figure 1:** Snapshot of the network layout used in VISSIM.

Following Ortigosa *et al.* (2015), a “demand node” was placed in the middle of each of the 24 main links, which was used to produce and attract cars in the network - acting as an origin and destination node.

A uniform demand throughout the network was ensured by having all demand nodes producing and attracting cars with the same probability. In other words, for a standardized case: all links had a demand node, which produced 23 vehicles, each going to one of the remaining 23 links during a period of 1 hour. In order to have a full coverage of the MFD, demands were chosen to range from 2.2 to 14.3 times the standardized case, i.e., demands range from around 1210 to 7890 trips an hour. The routes were assigned dynamically, according to the standard built-in dynamic traffic assignment (DTA) module in VISSIM 8, which follows roughly a user equilibrium principle. Details about the implemented DTA can be found in Ortigosa *et al.* (2015), PTV AG (2015).

A simulation warm-up time of 900s was used. The data from such period is excluded from analysis.

Two cases are differentiated for the vehicle composition: Either traffic in the network consists of only CVs or only AVs. In other words, the intermediate scenario, where CVs and AVs circulate at the same time, was disregarded.

3.3 Results

3.3.1 MFD

Fig. 2 shows two MFDs - one for each vehicle type, CVs and AV. The congested branch of the MFD was not simulated. First of all, we record a much higher capacity for the network with AVs only. This is not surprising, since the car flow in the system depends largely on the headway which is significantly lower for AVs than for CVs. Second, the density at which the flow is maximized (critical density) is higher for CVs. AVs also allow to reduce spacing, which explains these results. Average speeds remain the same up to a flow of 400 veh/h per lane. Then, the CV network starts to congest and reaches capacity at around 600 veh/h per lane (compared to 1550 veh/h per lane for AVs). Therefore, AVs greatly increase the capacity of an urban network, without even having touched capacity gains from connectivity at intersections, re-routing, or of possible platooning.

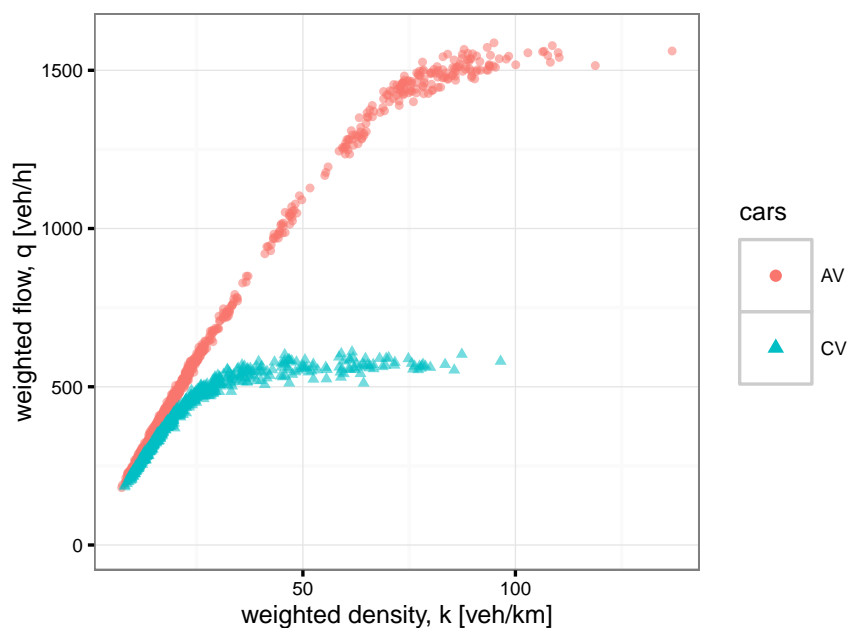


Figure 2: MFDs of non AVs and AVs.

3.3.2 Road Space

With eq. 3 we can evaluate the change in road space needed from CVs to AVs. Thus, fig. 3 shows the relative change in footprint for the mean of the 3 top MFD flow values for each level of demand. The demand is represented in the number of trips. As an example, for 2000 trips/h we do not change much the footprint of the vehicles when switching from CVs to AVs. However, for 2500 trips we would save around 4.5% of footprint per vehicle. As mentioned before, the comparison is only made for common demand levels. Thus, the comparison can be made up to the capacity of the CV network at around 3100 trips/h. Since vehicle footprints and road space

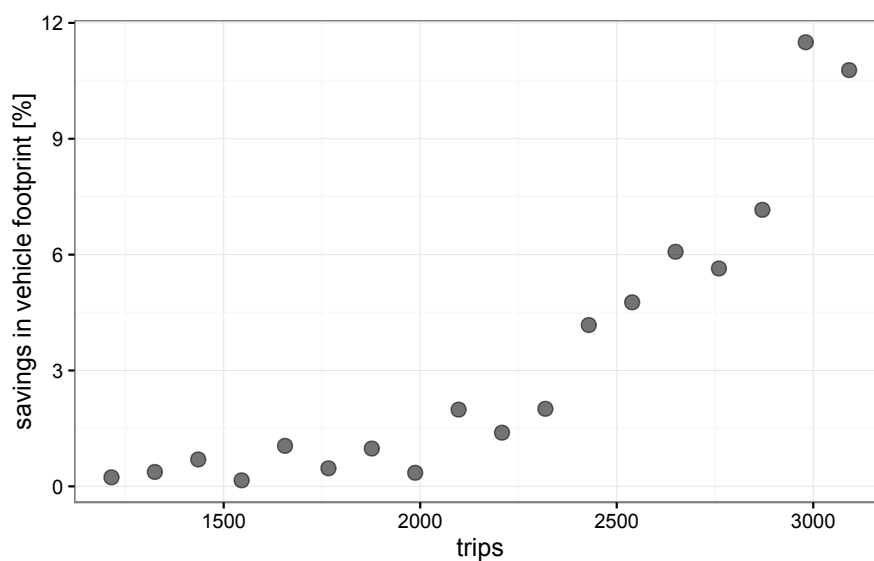


Figure 3: Vehicle footprint savings when switching from CVs to AVs.

usage are proportional for a given demand, we can deduce the road space usage change directly from fig. 3. At CV capacity, AVs would save around 11-12% road space. It is clear that we cannot just remove this amount of space without creating new bottlenecks. Still, this value gives a first insight. It can be imagined that the extra space provided at intersections and bottlenecks, which allows for some accumulation, could be rescaled.

When switching from CVs to AVs, we could ask, how many more trips the network can handle, while leaving the road space use at the same level. Thus, we multiply the number of trips with the footprint from eq. 2. For fig. 4 we introduce an *indexed* road space, where 1 is the maximum road space needed for CVs. Again, we analyse the 3 top MFD flow values for each level of demand. We added a linear regression for both, AVs and CVs. Generally, it makes sense that the more trips the network satisfies, the more road space it needs. The difference between AVs and CVs is at first almost non-existent. However, with increasing road space, a difference becomes visible: AVs are capable of carrying more trips than CVs with the same amount of road space. This is what we expect, since AVs are more efficient on road space usage. Fig. 4 makes it

possible to evaluate the number of additional trips made possible with AVs using existing road space: CVs in the network were capable of handling slightly more than 3000 trips an hour, with AVs instead, around 9000 trips an hour can be performed. This confirms the findings from the MFD comparison, where we showed that a much higher flow can be reached with AVs than with CVs.

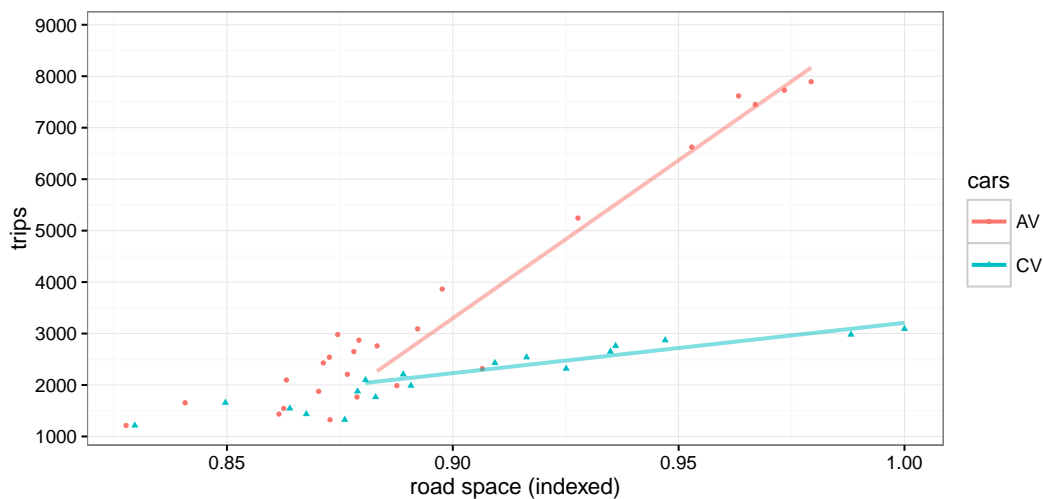


Figure 4: Road space used by CVs and AVs.

3.4 Conclusions

With recent developments in autonomous traffic, the interests in understanding the effects thereof on traffic operations and space allocation have grown. It is important to understand how road traffic interacts with road space. This paper analyses the impact of AVs on road space, based on a simulation and based on the conservative scenario that AVs will not communicate and be privately owned. We find that for the same amount of trips in a small grid network, AVs can decrease the road space needed by around 11-12%. However it would be challenging to remove this proportion of roads without creating actual bottlenecks, which would in turn reduce traffic flow. Given the existing road infrastructure, AVs potentially triple trips. These findings not only emphasize the effect that AVs will have on mobility, but also provide a insight into (road) space as a possible variable in the discussion on how AVs will impact traffic in urban areas. Space might be used as an additional leverage in the hands of policy makers in order to find new equilibriums between sheer functionality and social welfare.

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