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A traffic simulation study in The Hague, Netherlands**

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DOI

[10.1016/j.ijtst.2020.03.009](https://doi.org/10.1016/j.ijtst.2020.03.009)

Publication date

2020

Document Version

Final published version

Published in

International Journal of Transportation Science and Technology

Citation (APA)

Overtoom, I., Correia, G., Huang, Y., & Verbraeck, A. (2020). Assessing the impacts of shared autonomous vehicles on congestion and curb use: A traffic simulation study in The Hague, Netherlands. *International Journal of Transportation Science and Technology*, 9(3), 195-206. <https://doi.org/10.1016/j.ijtst.2020.03.009>

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Contents lists available at ScienceDirect

International Journal of Transportation Science and Technology

journal homepage: www.elsevier.com/locate/ijtst

Assessing the impacts of shared autonomous vehicles on congestion and curb use: A traffic simulation study in The Hague, Netherlands

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ARTICLE INFO

Article history:

Received 10 November 2019

Received in revised form 29 March 2020

Accepted 30 March 2020

Available online 15 April 2020

Keywords:

Autonomous vehicles

Shared autonomous vehicles

Urban traffic

Curb use

Simulation

ABSTRACT

New developments in the automotive world have the power to change mobility, but because of high uncertainties, municipalities are adopting a wait-and-see attitude. Nonetheless, autonomous, connected and shared vehicle technologies are in a far stage of development and it is only a matter of time before shared autonomous vehicles (SAVs) enter urban traffic. This research aims to provide insights into the congestion effects of SAVs on urban traffic, focusing on the differences in microscopic behaviour from conventional cars, and to investigate which easy-to-implement solutions a municipality could apply to facilitate the new mix of traffic. This was researched by performing a simulation study, using the traffic simulation package Vissim and a case study of a network in the city of The Hague during the morning peak in 2040. Several SAV market penetration scenarios were tested: 0%, 3%, 25%, 50% and 100% SAV usage by travellers. Additionally, two network designs were implemented: dedicated lanes for SAVs and kiss & ride (K&R)-facilities. From the results, it was clear that while the autonomous driving capabilities of SAVs help reduce traffic congestion, they also have a negative effect by stopping on the curbside to drop off passengers, forming bottlenecks for other road users, and by circulating on the network using low capacity links. Below the line, this adds up to an overall negative effect on urban traffic congestion according to our results. The dedicated lanes design was unsuccessful at reducing this congestion caused by SAVs. The K&R design, however, was successful at reducing delays, but only for SAV penetration rates higher than 25%. These exact effects are not generalizable due to limitations in network size and simulation software. However, the results can be seen as indicative for planning purposes. Similar effects could be expected in cities where transport network companies (TNCs) such as Uber become exceptionally popular with non-autonomous cars. The advice for municipalities is to closely monitor the situation and to account for SAVs (and TNCs) in each new infrastructural project.

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<https://doi.org/10.1016/j.ijtst.2020.03.009>

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1. Introduction

Just like they have one century ago, developments in the automotive industry are now at the verge of reshaping our idea of mobility, and society as a whole. The Dutch research institute for mobility, KiM, expects autonomous vehicles (AVs) and shared autonomous vehicles (SAVs) to reshape cities in the 21st century (Tillema et al., 2017). Autonomous and on-demand vehicles may start serving an increasing part of the growing transportation demand. SAVs will form the basis of commutes, errands and shopping trips. SAVs also form an excellent mode for first and last mile transit, as pointed out by the research of Scheltes and de Almeida Correia (2017). This could lead to a highly efficient and sustainable socio-technical system where higher mobility rates are achieved with fewer resources. However, KiM also presents some less positive scenarios where the tolerance for longer travel times causes high levels of road congestion and where the eternal struggle between safety and efficiency cripples the industry. Additionally, few studies mention what the driving behaviour of SAVs on the roads may mean for congestion levels and traffic circulation in general in urban areas.

How cities and their traffic will change exactly, is highly uncertain. However, just like in the beginning of the twentieth century with the introduction of the automobile, early adaptation and intervention by municipalities is crucial in determining how SAVs may affect urban traffic and mobility in general. One thing is certain: autonomous and shared vehicle technologies are in a far stage of development and it is only a matter of time before SAVs enter urban traffic. What this will mean for traffic is still unclear.

The goal of this research is twofold: firstly, to provide insights into the congestion effects of different penetration rates of SAVs in urban traffic, focusing on the differences in microscopic behaviour as compared to normal cars, and on the urban main road network. Secondly, to investigate how the municipality could intervene using easy-to-implement solutions to facilitate the new mix of urban traffic that can be expected in the future.

In this paper, the main input and findings of this research are presented and discussed. In paragraph 2, the findings of the literature review are discussed. In paragraph 3, the research methodology is presented, after which Section 4 outlines the application of this methodology. The results are discussed in Section 5. Finally, conclusions, limitations and recommendations for further research are presented in Section 6.

2. Literature review

Road congestion typically occurs when the traffic intensity exceeds the road's capacity (Wardrop, 1954). Traffic intensities are the result of an array of human choices constituting travel demand. The road capacity for urban roads is quite tricky to determine. Urban roads are designed in such a way that they provide a good balance between access to the lower level road network and surrounding real estate, and adequate traffic throughput. KpVV CROW (KpVV CROW, 2017b), an independent Dutch knowledge institute that performs research and writes guidelines on design and policy for traffic-related issues, introduced a ranking of Dutch urban roads where the emphasis in higher levels is more on throughput, while the emphasis in lower levels is more on access. This is because road elements that improve accessibility, reduce a road's capacity: low speed limits, roadside activity, interaction with other vehicles, and traffic control.

Personal AVs and SAVs can potentially influence congestion in urban traffic both in terms of traffic intensities, and in terms of road capacity. The road capacity is influenced by the differences in driving behavior between AVs and normal cars. Especially the differences in headway play a large part in this. Traffic intensities are influenced on a microscopic level by these changes in road capacity and on a macroscopic scale by travel demand effects. Both are dependent on how the market develops and thus on how the penetration rates of personal AVs and SAVs in urban traffic evolve. Therefore, market penetration scenarios were formulated for this research, and macroscopic and microscopic effects were further investigated in this literature review.

2.1. Market penetration personal AVs and SAVs

Many researchers have attempted to study market developments in vehicle automation and forecast future penetration rates. According to Milakis et al. (2017), who formulated market scenarios with a panel of experts, full AVs will be introduced in the market somewhere between 2018 and 2045, with penetration rates between 10% and 71% by 2050. Litman (2018), who bases himself on earlier automotive developments, believes this market introduction will likely be before 2030, with new car sales of 30% by 2040 and 50% by 2050. Finally, Nieuwenhuijsen et al. (2018), who conducted a quantitative system dynamics study, came to the conclusion that market penetration by 2040 should be somewhere between 3% and 66%, and between 5% and 90% by 2050. The bandwidth of the AV and carsharing penetration rates is high. This is because there is high uncertainty in technological development, willingness to invest and public adoption. These penetration rates found here were used for the formulation of scenarios for this study. Clearly the bandwidths are very wide, indicating a high uncertainty in the market development.

Market research about SAVs is less straightforward, as it mostly targets the vehicle sharing market in general, while this research is focused on shared *autonomous* vehicles only. According to figures from KpVV CROW (KpVV CROW, 2017a), regular vehicle sharing is gaining popularity quickly in The Netherlands, especially in urban areas where in 2017 there were almost 400 shared cars per 100.000 inhabitants. The European Commission is very enthusiastic about what the combination

of vehicle automation and sharing could mean for urban mobility, and has set as a target that by 2030, 25% of all urban trips should be performed by a SAV (European Commission, 2018). In formulating the scenarios for this study, these notions were taken into account.

What all researchers agree on, is that new mobility concepts, like automation and sharing, reinforce each other. Indeed, vehicle sharing becomes much easier when the vehicles are autonomous, and can drive themselves to your doorstep and to the next customer. Therefore, a positive correlation is expected between the market development of these technologies. This correlation was taken into account when formulating the scenarios for this study.

2.2. Macroscopic effects of AVs and SAVs

The focus of this research is on the microscopic on-road effects of AVs and SAVs. However, these new mobility options may also have macroscopic effects which are important to note. To understand how demand and distance travelled is influenced by the availability of new mobility options, it is important to understand the working principles of the 4-step transportation model as explained in de Dios Ortuzar and Willumsen (2011) and interactions between land use and mobility as explained by Wegener (2014). The essence of these works is that low generalized transport cost with a specific mode to a certain location will induce travel demand to this location. Generalized transport costs are usually defined as the price per kilometre multiplied by the access distance plus the traveller's value of travel time savings (VOTT) multiplied by the travel time to the location. Using a discrete choice experiment, de Looft et al. (2018) found that the VOTT for AVs lies around 25% lower than for conventional vehicles, albeit depending on what can be done inside. Further, Fagnant and Kockelman (2015) found that additional savings on the generalized transport cost of AVs are achieved as a result of better fuel efficiency, parking benefits, and crash savings. All these cost reductions could mean that AVs may induce significant numbers of travel demand. This is an important notion to take into account when interpreting the results of AV studies like this one.

How SAVs may influence travel demand and congestion, is less straightforward, and is determined by the SAV demand, fleet size, vehicle occupancy and vehicle kilometres (VKT). If SAV demand is only coming from travellers who previously travelled with their own car, like Litman (2018) is suggesting, this will mean little to nothing for total travel demand. However, other researchers, like Martinez and Viegas (2017), acknowledge that the attractiveness of having a door-to-door transport option at a low trip price and having all the advantages of general AVs, may induce extra demand. How this demand is satisfied, is dependent on a city's fleet size and average vehicle occupancy. Fagnant and Kockelman (2016) found that impacts of this induced demand on road congestion can be reduced by combining a good strategy of determining the needed fleet size with good strategies for sharing rides of multiple passengers, increasing the vehicle occupancy. However, negative effects on road congestion are also expected as SAVs cover a lot more distance than normal vehicles would for the same trips. This is due to repositioning and empty kilometres (Fagnant and Kockelman, 2014). What is remarkable, is that the researchers only comment on the sheer extra distance driven, without taking into account the fact that the way in which SAVs may circulate the network may differ from what the network was designed for, and may therefore have negative effects. This is the focus of our study.

2.3. Microscopic effects personal AVs and SAVs

As mentioned earlier, this research focuses on the microscopic effects of personal AVs and SAVs on urban traffic. This is partly because there is little knowledge about these effects. And research that *does* investigate this topic, does not seem to reach a consensus about whether the effects on traffic congestion are positive or negative. Therefore, it is useful to first look at how exactly the driving behaviour of personal AVs and SAVs differs from conventional cars before conclusions are drawn about the microscopic effects.

When looking at longitudinal and lateral driving behaviour, Saleh et al. (2013) and González et al. (2016) report that the advanced sensor systems and control algorithms greatly reduce stochasticity in the driving behaviour of AVs, having a positive influence on road congestion. Additionally, Bose and Ioannou (2003) argued that the acceleration and deceleration of AVs is conducted in a much more smooth fashion, also allowing them to filter out turbulent behaviour of other vehicles. However, several researchers including Ioannou and Stefanovic (2005) and Calvert et al. (2017) drew a less positive image by stating that sensor technologies, while reducing stochasticity in the AVs behaviour, may lead to longer headways and more turbulence due to cut-ins. But if this is complemented with connected technologies, Talebpour and Mahmassani (2016) argue that the AVs are additionally able to generate a much wider view of the traffic, allowing them to drive closer to each other, reacting faster and in a much smoother fashion. All in all, the driving behaviour of AVs could be summarized as presented in Table 1. The characteristics mentioned in this table were used to define the behaviour of the vehicle classes in the simulation model. These behaviours are expected to improve traffic flow, thereby increasing the road's capacity.

For SAVs it was much more difficult to find literature about their expected driving behaviour. Apart from being AVs and therefore also displaying all the AV driving behaviour characteristics as described above, some other behaviour is also expected. Firstly, Fagnant and Kockelman (2014) earlier already predicted that SAVs would cover more distance than conventional vehicles because of empty kilometres and repositioning. However, they did not mention that this likely involves circulatory movements, using links and traffic signals that do not have sufficient capacity. This could cause disproportionately long queues and delays. Secondly, if people are being picked up and dropped off alongside the road where there is no curbside parking space available, this will form temporary bottlenecks. The International Transport Forum (International Transport Forum, 2017) dedicated a study to how curbside use is changing as a result of the modal shift from personal modes

Table 1
Differences in driving behaviour AV.

Factor	Difference from conventional car
Time headway	Shorter, lower deviation
Distance headway	Shorter, lower deviation
Speed	Less deviation
Reaction time	Shorter, lower deviation
Lookahead distance	Further
Acceleration/deceleration	Smoother, lower deviation
Path deviation	Smaller

to shared modes of transport. They predicted that the use of shared modes will put the curbside under increased pressure due to curbside stopping, loading/unloading and parking of free-floating shared vehicles like bicycles and scooters. This in addition to the long-term roadside parking that is already taking up a lot of space. Together, this can have negative consequences for other curb users as well as on-road traffic.

Upon close inspection, personal AVs and SAVs also represent the above described trade-off between high traffic throughput and high accessibility. Where personal AVs may improve traffic throughput, increasing a road's capacity, SAVs may provide a higher level of access to surrounding real-estate, thereby decreasing the road's capacity. This trade-off is visualized in Fig. 1. These effects were inspected more closely in this research by means of a simulation study, which is described in the next section.

3. Methodology

A modeling study was performed consisting of two parts: a scenario study and a design study. The purpose of this modeling study is to obtain detailed and quantitative insights into what happens to urban traffic when currently non-existent vehicle types are introduced. For the model input in terms of demand, market penetration, vehicle behaviour, and designs, a literature review was performed. Realistic market penetration scenarios were formed, determining the presence of non-autonomous vehicles, personal AVs and SAVs. Then, a conceptual model was formulated, sketching the expected relationships between model input and model output.

Afterwards, a simulation model was specified using the traffic simulation software Vissim, in an attempt to quantify these relationships. A case study network was chosen in the city centre of The Hague that contains an urban main road linking the national road network to the lower level road network. The area in which the network is contained is around 3 km long and 2 km wide. It contains four signalized and six unsignalized intersections for motorized traffic. Since a simulation model of this network was already available, an adaptation was required to implement personal AVs and SAVs. The original dynamic simulation model was built by Arcadis. They used traffic demand generated by the official regional traffic model V-MRDH 2.4, of which traffic generation, modal split and trip length are calibrated using real-world counting data and validated by the municipality of The Hague. As a modeling year, 2040 was chosen, and as time of day the morning peak period was chosen. 2040 is used as reference year, because it is mentioned in a lot of literature as an important time horizon, for example for carbon emission reductions. Furthermore, this time horizon made it possible to make sufficiently accurate estimations about AV and SAV penetration rates.

First, a set of scenario studies were performed to investigate the effects of different penetration rates of personal AVs and SAVs. Then, a set of network designs were defined, modeled and tested in the design studies. The designs were based on a set of easy-to-implement solutions which the municipality could apply to facilitate the new vehicle types without having to change the infrastructure too much. As findings in later stages of the study also informed inputs for the earlier stages, the entire process was an iterative one.

4. Application

The behaviours of personal AVs and SAVs that were found in the literature, were combined and translated into a conceptual model for this research. This model was then built using the traffic simulation software Vissim and a case study of a



Fig. 1. Trade-off between network access and traffic throughput with AVs and SAVs.

network in The Hague during the morning peak in 2040. Vissim includes standard sets of driving behaviour parameters which are based on research by Wiedemann (1991) and Wiedemann (1974) and calibrated using empirical data from German drivers by Fellendorf and Vortisch (2001). The behaviour sets that were defined for AVs and SAVs were deduced from those standard sets. Changes were made based on research performed in the research project RoTraNoMo (PTV Group and Volkswagen, 2005) and validated using empirical data from the University of Karlsruhe and the University of Aachen. Lacking better information, it was decided to leave these parameters active, knowing that more research should be done in the future. The first part of the study focused on finding the effects of different market penetration scenarios, and the second part focused on finding the effects of two easy-to-implement designs of urban infrastructure.

4.1. Scenario studies

Based on what was found in the literature, a set of 7 scenarios were established with regard to the penetration of personal AVs, percentage of travellers using SAVs, and average occupancy of SAVs. Additionally, assumptions were made based on the literature and real life data with regard to the base demand, and the behaviour of the personal AVs and SAVs. An overview of the scenarios is presented in Table 2. The names of the scenarios are uniformly structured to signify the penetration of personal AVs out of all personal vehicles and the share of travellers that are travelling to the case study area in a SAV. The formatting is as follows: <penetration personal AVs>/<penetration SAVs>.

A conceptual model was formulated outlining the expected relationships between the input and output variables. It was expected that a higher penetration of personal AVs would increase the road capacity and reduce variations in traffic flow. This would in turn reduce vehicle delays and emissions. On the other hand, it was expected that a higher penetration of SAVs would reduce road capacity due to curbside stopping, increase traffic intensity and the demand/capacity ratio of traffic lights due to (empty) circulation on the network, and increase variations in traffic flow. All this was expected to lead to an increase in vehicle delays, an increase in distance travelled, and an increase in emissions. These effects were expected to be slightly reduced when SAV occupancy was increased, simply by a reduction in traffic intensity. The car travel demand was also included as an external factor in the conceptual model that could influence the system by increasing traffic intensities and thereby the total distance driven, and the vehicle delays. The influence of the car travel demand in the simulation model, however, was reduced to a minimum in order to provide a clear view of the effects due to differences in driving behaviour.

The above described behaviours of personal AVs and SAVs were translated into specific vehicle classes in Vissim. The autonomous driving characteristics of the vehicles could be modeled by adjusting a set of parameters of the built-in driving behaviour models and distributions. The most important parameter changes in this research were shorter headways, shorter reaction times, shorter standstill distances, longer lookahead distances, and no stochasticity in desired speeds, acceleration and deceleration. As mentioned above, these parameter changes were based on research by software provider PTV.

The behaviour of the SAVs was modeled by selecting a certain amount of AVs (therefore including the AV driving behaviour characteristics) that were going to drop off a passenger in the network. These vehicles would then drive to their drop off location, idle for a certain amount of time to allow the imaginary passenger (there are no physical passengers in the model) to get out, and then continue to a next destination somewhere outside the network. To allow for this, 21 drop off locations were selected where SAVs would logically often drop off passengers if not regulated. Seven of these had curbside parking spaces available. Fig. 2 shows a cut-out of the network with the original SAV stopping locations and points of interest at the roadside.

The vehicle classes that were modeled as non-autonomous and AVs, were cars, light freight, heavy freight and buses. The vehicle classes that were modeled as SAVs, were only cars.

Instances of the resulting vehicle classes were loaded onto the network at different penetration rates based on the scenarios. The base demand was equal for all scenarios and was obtained by extrapolating car trip generation that was derived from the static demand model V-MRDH for The Hague for 2030. The extrapolation rate was based on the average annual growth in The Hague and spread unevenly over the morning peak period to account for network saturation in the middle of the peak.

The model was verified by comparing measurements of traffic intensities and animation of vehicle behaviour with the model input as defined in the conceptual model. This was done for non-autonomous vehicles as well as AVs and SAVs. Figs. 3

Table 2
Scenarios.

Scenario	AV (% of vehicles)	Shared (% of travellers)	Avg pax SAVs (# pax)	Buses
1. 20/3	20%	3%	1.1	AV
2. 50/25	50%	25%	1.5	AV
3. 80/50	80%	50%	2	AV
4. 0/0	0%	0%	N/A	Normal
5. 50/0	50%	0%	N/A	AV
6. 100/0	100%	0%	N/A	AV
7. 100/100	100%	100%	2	AV

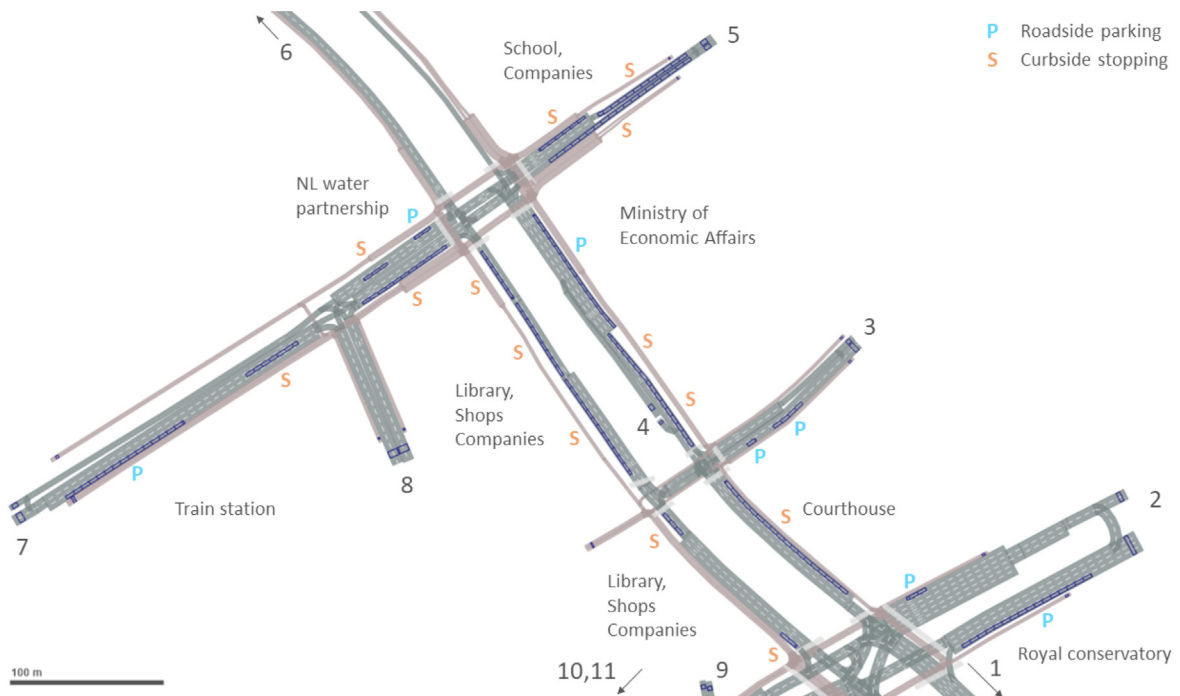


Fig. 2. Stopping locations SAVs, places of interest, and O/D zones.

and 4 show the behaviors of AVs and SAVs in the model in terms of standstill distance, headways, stopping behavior and network circulation.

As there was no real-life data to compare the results to, model validation was done by expert validation and sensitivity tests. Six experts from the Municipality of The Hague, Delft University of Technology and Arcadis, active in the fields of transport policy, traffic engineering, transport simulation and intelligent transport systems were interviewed. They were shown the model animation and results based on 5 runs, and asked for their thoughts on its plausibility. Within the scope of the study, the model and its results were deemed plausible. One suggestion was to create more differentiation in the behavior of non-autonomous vehicles in the model to create a more life-like situation. This was done by creating three sets of desired speed distributions and acceleration/deceleration functions: for defensive, normal and assertive drivers.

For the sensitivity tests, four factors were studied: the base demand, the headway of AVs, the amount of deviation between human drivers, and the dwell time of SAVs when they drop off a passenger. The model was found to be especially sensitive to the values for the car travel demand and the AV headway. Higher values for both factors, caused higher vehicle delays. Therefore, it should be taken into account that when interpreting the results, different values for these factors in reality could yield different results.

The required number of simulation runs was determined by comparing a subset of 20 replications with a subset of 30 replications for each scenario to see whether convergence was reached. It was established that convergence was already reached at 20 replications. But since there was a set of 30 replications available, 30 replications were used to base the results on. After model verification, model validation and determining the experimental set-up, results could be retrieved.

4.2. Design studies

To reduce the expected negative effects of SAVs while still providing them access to surrounding real estate, the municipality might need to undertake action. However, in the transition period, it is desirable to keep adaptations to the road infrastructure to a minimum and limit initial investments. Therefore, two easy-to-implement designs were defined and their effectiveness was tested. The first is a design where the main road is expanded by one lane on the curbside, which then becomes a dedicated lane for SAVs and buses. SAVs may stop on this lane wherever they want. The second is a design where kiss & ride facilities are built on the roadside of the lower level roads, diverting SAVs from the main road.

The designs were also included in the conceptual model of expected relationships between in- and output. It was expected that the dedicated lane design may have a positive effect on traffic throughput, because the capacity of the road is increased and the problem of SAVs stopping on the road, forming bottlenecks for other vehicles, is solved. Further, it was expected that the distance driven by SAVs could be reduced, because they can drop-off their passengers centrally in the network. However, it was also expected that a negative effect may be an increased amount of weaving movements

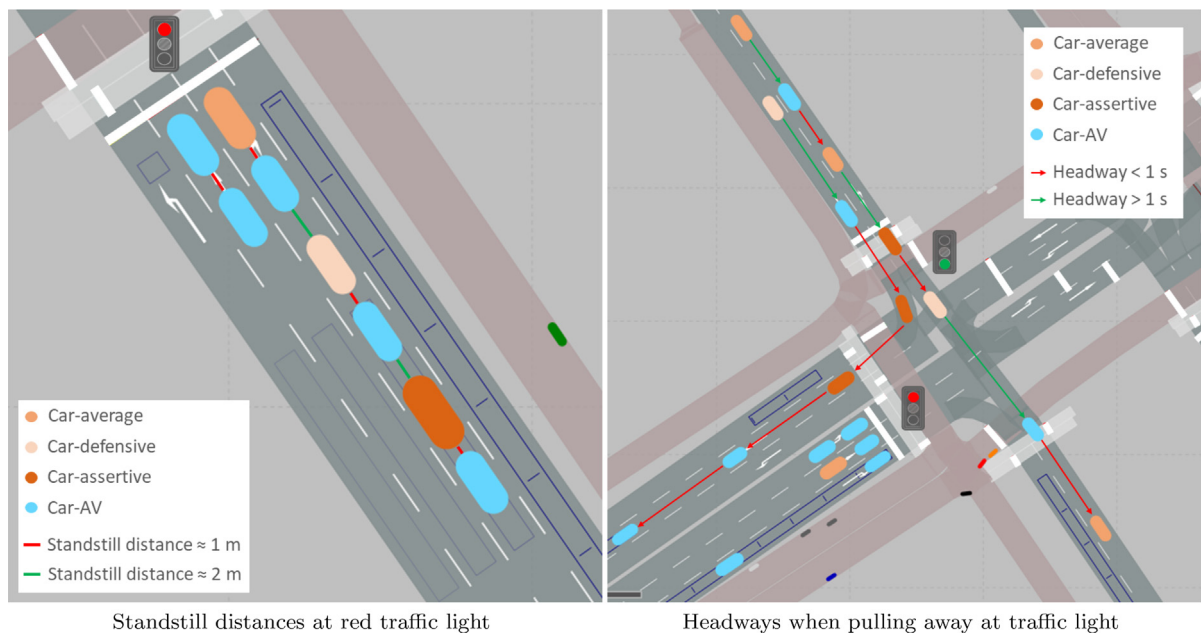


Fig. 3. Standstill distances and headways of different vehicle types.

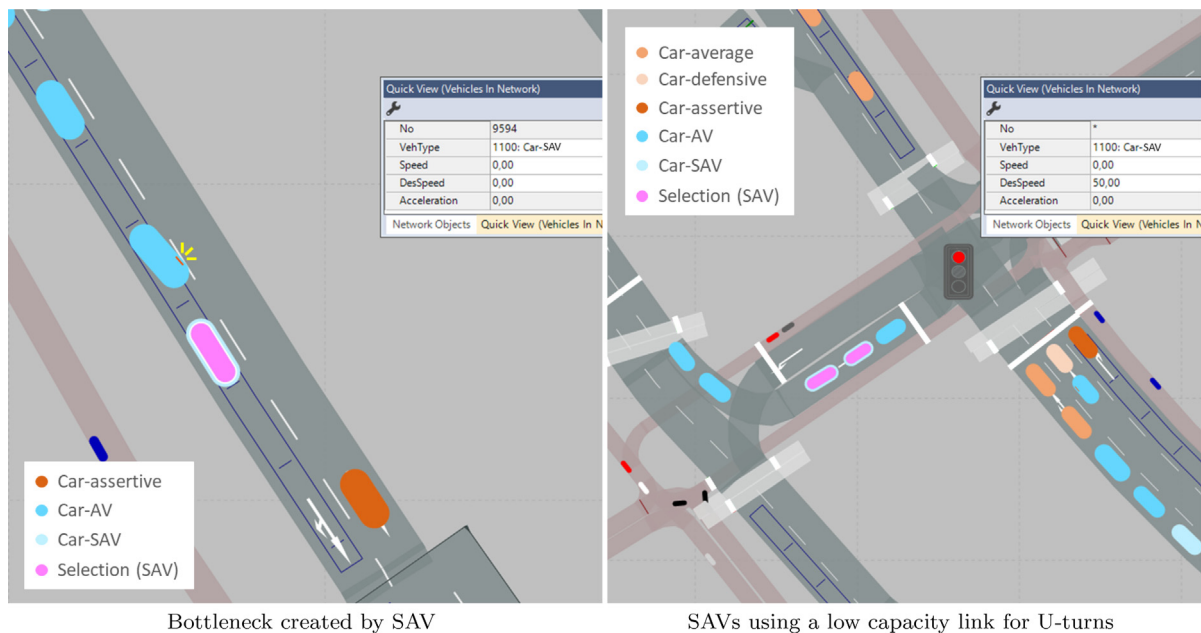


Fig. 4. Behaviour of SAVs in the Vissim model.

on the main road, and the SAVs still using low capacity links to make U-turns on the main road. The kiss & ride design was expected to have a positive influence on the congestion by leading the SAVs away from the main road, preventing usage of low capacity links, and mandating them to stop on the side of the road, thereby not forming bottlenecks for other road users. However, this design was expected to increase the distance that SAVs drive, as they are sent to less central locations.

The designs were implemented in the simulation models of the four scenarios with different penetration rates of SAVs: scenarios 1 (20/3), 2 (50/25), 3 (80/50) and 7 (100/100). In these simulation models, the road infrastructure and vehicle routing was slightly changed. However, the changes were only minor, as these are easy-to-implement solutions. After defining the experimental set-up, results could be retrieved.

5. Results

To get a full grip on the congestion effects, results were retrieved from the model in terms of average vehicle delays, distance driven and emissions. Vehicle delays were measured by looking at the difference between each car's "ideal" travel time (under free flow) and the actual travel time over four representative routes. These were routes with both a high amount of traffic and a high usage of the entire network. To account for the fact that differences in delay could be attributed to a possible increase or decrease in intensity on the network, the total distance driven by all vehicles was reported and compared between cases. Furthermore, average emissions per kilometre driven were retrieved with the help of the Enviver Pro module, an analysis tool developed by TNO that combines traffic simulation output with emission models. This was done to verify that differences in delay were due to differences in turbulence of the traffic flow as a result of the driving behaviour of personal AVs and SAVs. The idea behind this being that an increase in traffic flow turbulence causes an increase in energy consumption of all vehicles, which can be measured by means of measuring the emissions per kilometre.

It was found that in all cases, high or low delays came paired with high or low emission levels per driven kilometre, and the total distance driven hardly ever differed significantly. Therefore, it could be concluded that the delay values that were found purely represent the congestion effects of the driving behaviour shown by personal AVs and SAVs. The delay values for non-SAV motorized vehicles as well as SAVs are presented for each scenario and each design in Table 3. In this table, a distinction is made between non-SAV motorized vehicles (cars, HGVs and LGVs, either human driven or AV) and SAVs. This is because SAVs spend more time in the network by default, as they need to drop off passengers. Combining these vehicles with other vehicles, would give an unrealistic idea of the effects. The same is done for the emissions results, which are presented in Table 4.

The results for the delay contracted by non-SAV vehicles will be used as the main indicator for interpretation of the results in terms of congestion effects. This is because these vehicles represent the "normal" traffic. Furthermore, including the delay times of the SAVs in the analysis would give a distorted image of the facts, because their delay time includes dropping of their passenger and they do not take the shortest route from where they enter the network to where they exit the network. The SAV delays, however, do contain valuable information about the amount of delay contracted while detouring for each scenario and design. The non-SAV delay results are depicted in two figures. Fig. 5 depicts the relative delay contracted by non-SAV vehicles for each scenario. The size of the bubble is an indication for the relative delay. The scenario factors are on the axes. Further, propagation of the delay contracted by all non-SAV motorized vehicles per scenario is plotted in Fig. 6. In this figure, the average delay per 15 min time interval is plotted for each scenario.

5.1. Effects of personal AVs

The results confirmed the hypothesis that an increase in the amount of personal AVs on the road reduces congestion significantly. This could be concluded from low delays in scenarios 5 (50/0) and 6 (100/0) with personal AVs but no SAVs as compared to scenario 4 (0/0) with neither personal AVs nor SAVs. Additionally, the emissions values in this scenario were much lower, indicating lower energy consumption per kilometre with the total distance driven remaining the same. This implies that the reduction in delay is truly an effect of less turbulent, more efficient driving behaviour of AVs.

5.2. Effects of SAVs

The presence of SAVs yielded less positive results. Scenarios with realistic amounts of SAVs in addition to personal AVs (scenarios 1, 2 and 3) still showed a reduction of delay as compared to scenario 4 with no personal AVs and SAVs, but not as much as the scenarios without SAVs. Furthermore, scenario 2 (50/25) performed significantly worse than scenario 1 (20/3) with regards to vehicle delay. Scenario 7 (100/100) where all travellers made use of SAVs showed the highest levels of delay. In this scenario, the delays were so high that not all vehicles had been able to enter the model by the end of the simulation period. When checking the distances and emissions, to see whether these delays were due to an increase in intensity or due to the on-road driving behaviour of the SAVs, it could be seen that the total distance had not significantly changed between scenarios and the emissions per kilometre had significantly deteriorated. In addition to a high average delay over the entire

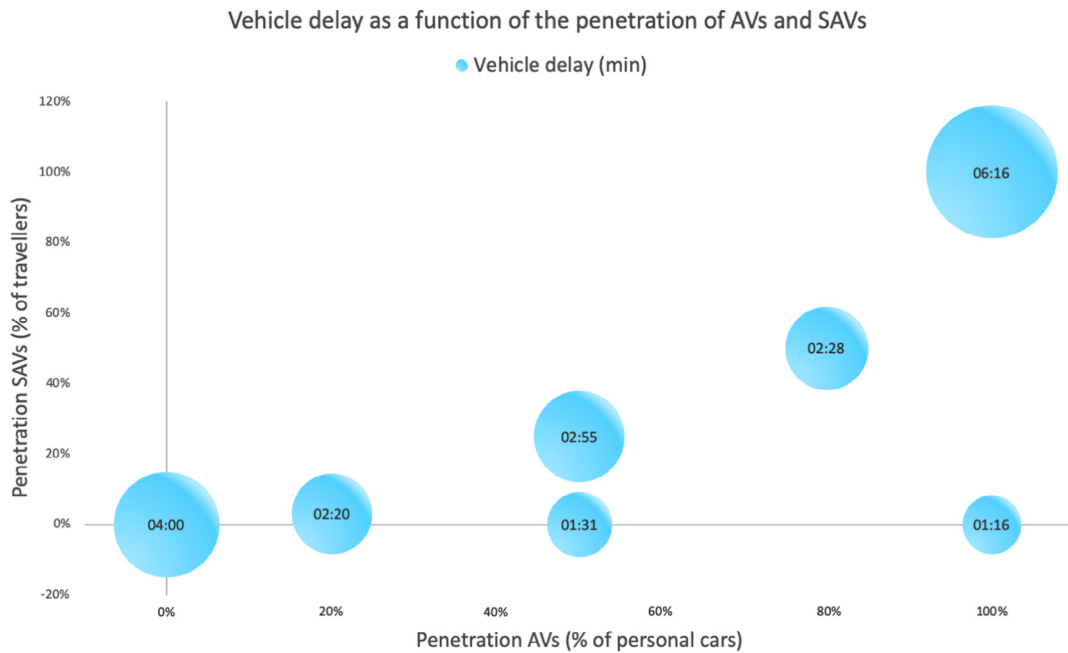
Table 3
Scenario and design results for vehicle delays of non-SAVs and SAVs.

Scenario/design	Non-SAV mean delay (mm:ss)			SAV mean delay (mm:ss)		
	None	Dedicated lanes	K&R-facilities	None	Dedicated lanes	K&R-facilities
1: 20/3	02:20	02:36	02:32	03:43	04:27	04:05
2: 50/25	02:55	02:50	02:50	04:00	04:22	03:49
3: 80/50	02:28	02:11	01:59	03:35	03:41	03:06
4: 0/0	04:00	–	–	–	–	–
5: 50/0	01:31	–	–	–	–	–
6: 100/0	01:16	–	–	–	–	–
7: 100/100	06:15	05:50	03:36	09:15	09:52	04:36

Table 4

Mean emissions per kilometre travelled designs

Design/scenario 20/3	CO ₂ (g/km)				NO _x (g/km)				PM ₁₀ (g/km)			
	1 50/25	2 80/50	3 100/100	7 20/3	1 50/25	2 80/50	3 100/100	7 20/3	1 50/25	2 80/50	3 100/100	7 20/3
None	292	301	292	345	0.453	0.467	0.450	0.565	0.041	0.042	0.040	0.048
Dedicated lanes	299	306	301	341	0.465	0.476	0.470	0.556	0.042	0.042	0.042	0.048
K&R- facilities	295	301	291	311	0.459	0.467	0.447	0.489	0.041	0.042	0.040	0.043

**Fig. 5.** Vehicle delay of non-SAVs per scenario depicted as bubbles. Bubble size indicates relative delay.

2-h morning peak period, Fig. 6 also seems to indicate that the delays do not start to decrease at the end of the peak. This is the case for all non-SAV scenarios.

These findings confirmed the suspicion that the delays were a result of the drop-off and circulation behaviour of the SAVs. Firstly, SAVs that stop to drop off a passenger could hold up traffic. In current traffic situations this already happens fairly often in the city, but when more travellers start using SAVs, the occurrence will highly increase. Secondly, in the process of combining different rides into a route, SAVs may circulate empty on the network. The sheer empty distance that they cover is not so much a problem, but the way in which they circulate the network may be. This is because finding the shortest route may imply making U-turns and using links which are not designed for a high amount of traffic. When these links become saturated, it may cause disproportionately long queues on upstream links.

As mentioned in the literature review, urban roads are designed for conventional cars to provide a certain combination of throughput and access, depending on the road level. As personal AVs provide a higher level of throughput and SAVs provide a higher level of access, but neither in the way that conventional cars do, solutions are needed to help restore the balance.

5.3. Effects of designs

After implementing the two designs in four scenarios with varying penetration rates of SAVs, it was found that the dedicated lanes design was unsuccessful in reducing the delays and emissions, even though the distance driven by SAVs was significantly reduced with this design. Despite the fact that this design implied an increase in the road's capacity, the increase in weaving movements and the increase in U-turns taken on the main road had a negative effect on the vehicle delays and emissions to the extent that the values for these KPIs remained statistically equal for the non-SAV motorized vehicles. The delays for the bus even increased with this design. This is due to the fact that the SAVs share the dedicated lane with the bus, which can therefore be held up by stopping SAVs. When studying the simulation runs of this design, it can be seen that while the secondary roads are less congested, SAVs are more concentrated on the main road where congestion is

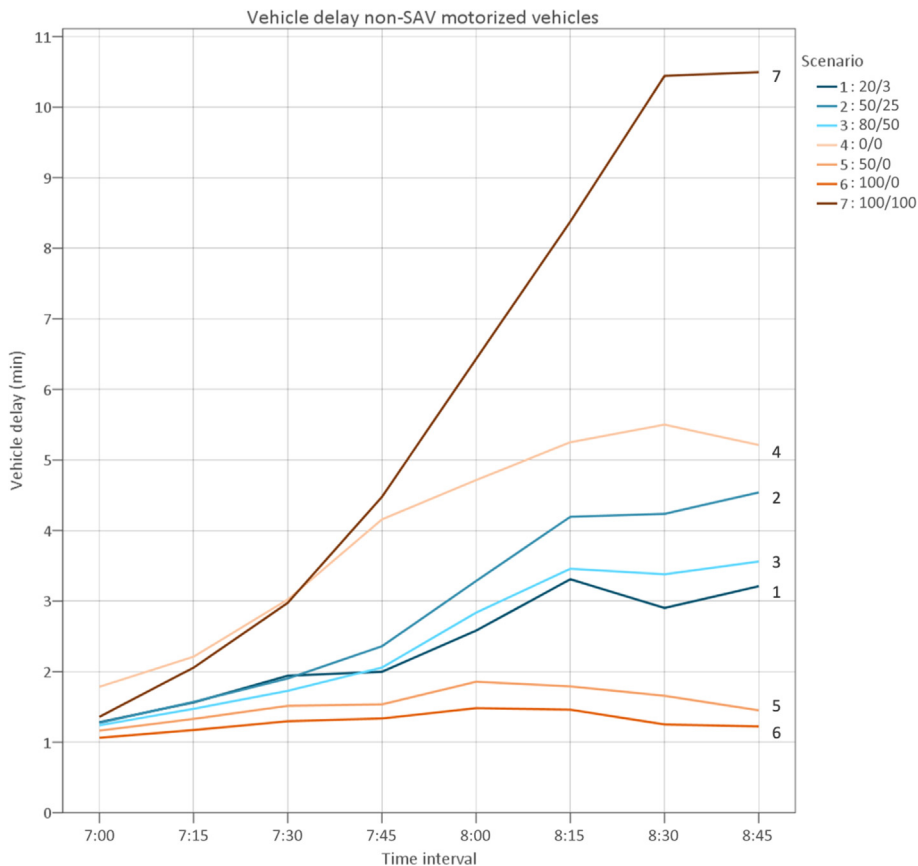


Fig. 6. Propagation of vehicle delay of non-SAVs over morning peak for 7 scenarios.

increased by SAVs that are slowing down, making weaving movements and making U-turns. This amount of congestion is very undesirable for the main road.

The K&R design, on the other hand, turned out to be an effective measure to reduce delays caused by SAVs. However, this was only the case when the penetration rate of SAVs was higher than 25% of the travellers. It is likely attributable to the fact that for SAV penetrations below 25% the negative effects of SAVs are not very strong yet. Effects that this design had on the distance travelled and emissions were only noticeable in the extreme scenario of 100% market penetration of SAVs. The positive effects associated with this design can be attributed to the fact that the SAVs are led away from the main road, where less traffic is hindered and where they stop on the side of the road. Additionally, the amount of U-turns made on the main road, using low capacity links, are kept to a minimum. This way, the traffic lights can easily process the queues that are formed. When studying the simulation runs of this design, it is noticeable that while a small amount of congestion appears on the secondary roads due to a higher concentration of SAVs there and the parking movements that the SAVs make, the traffic flow on the main road remains largely intact, because it is only used by SAVs to reach destinations on the lower level network.

6. Conclusions

Following the results from the scenario studies and the design studies, it could be concluded that cities with similar networks to the case study (ie. an urban main road where high traffic flow is combined with accessibility functions and interactions with other traffic is controlled by signalized intersections), can expect personal AVs to have a positive influence on the traffic flow here, reducing congestion. However, SAVs, which are likely to gain popularity together with personal AVs, can have a negative influence on road congestion by forming blockages, causing turbulence in traffic flow and causing queues on low capacity links. The results that were obtained for this case, not only illustrate the relationships that were proposed in the conceptual model, but also emphasize the conflict that is present on urban roads between the throughput function and the access function.

These results are interesting, because they fortify the suspicion that it is conceivable that SAVs could have a negative effect on urban traffic when implemented in the current situation. Indeed, the results of this simulation study point out that

there is a need to regulate the behaviour of SAVs in terms of drop-off locations and network circulation for the case under study. Given the available data for this case study, two easy-to-implement solutions were tested.

The research pointed out that these negative effects might be reduced by facilitating the SAVs with a fine-meshed network of kiss and ride-facilities on the sides of the underlying road network. However, the results suggest that this will only become effective at higher penetration rates of SAVs. As the research already detects negative effects at lower penetration rates, it is advisable to perform more research on solutions that will work when less than 25% of travellers are using SAVs. The results of this research suggest that effective solutions can be found in diverting the SAVs away from the main roads, to preserve its throughput function.

This research targeted shared vehicles that are autonomously operated. But practically speaking, similar effects could be expected in a city where transport network companies (TNCs) such as Uber become exceptionally popular without the necessity of the vehicles being autonomous. However, two properties of autonomous vehicles were found in the literature that make these effects less likely with non-autonomous vehicles and more likely with AVs. Firstly, the reduction in cost and other benefits that come with the absence of a driver can help accelerate the popularity of car sharing to a penetration that is needed for these effects. Second, the computer that is responsible for driving an autonomous car is more likely to make less sensible choices in terms of stopping.

Besides the above mentioned recommendations that specifically target the problems found in this research, it is advisable for municipalities to be cautious and closely monitor the situation when it comes to SAVs in their city. As these are new technologies and concepts, many other unexpected problems could occur like the ones found in this research. Furthermore, technological developments and market adoption are moving at a fast pace. Adopting a wait-and-see attitude in this could prevent the city from being able to benefit from these new mobility concepts or could even be potentially harmful. Therefore, it is advisable to pay attention to the impacts of SAVs in all future infrastructure plans.

There is a lot more research needed into AVs and SAVs before their effects can truly be known. Limitations of this study for which further research is recommended are roughly related to forecasting, model conceptualization and model specification.

There are many uncertainties when it comes to the technological and market developments of (S) AVs. Therefore, assumptions had to be made with regards to the demand effects and the driving behaviour of these vehicles. From the sensitivity tests, the model was found to be especially sensitive to the base demand and the AV headways. If these factors turn out to have a higher value in reality, this could have negative effects on congestion. The industry and mobility market should be closely monitored to see how these assumptions will relate to reality.

A model is always a simplified version of reality. Therefore, simplifications have to be made. With each simplification, a piece of information is lost. Important simplifications made in this research relate to the translation of demand forecasts and market penetration into OD matrices, the vehicle behaviour, and the network usage of SAVs. With regards to the vehicle behaviour, the model relies on calibration efforts by PTV Group which for normal cars is based on German empirical data and for AVs is based on the limited theoretical data available. With regard to the network usage of SAVs no calibration was performed. Consequently, the results of this study must be seen as indicative for planning purposes.

Finally, the use of the case study limits generalization of the results to parts of cities with similar networks. Furthermore, the network under study is of a very limited size. The effects of AVs on congestion and emissions could, for instance, be very different for a network with single lane roads, direct interaction with cyclists and unsignalized intersections.

Acknowledgement and conflict of interest

This article is based on the research work that the first author has done for her master thesis at the Delft University of Technology. This thesis was the last step to obtain a masters degree in Transport, Infrastructure and Logistics. The research project was commissioned by the engineering and consulting firm Arcadis who might use the results to consult municipalities on how to prepare for autonomous vehicles. At the university, my supervisors were Prof Alexander Verbraeck and Dr. Yilin Huang from the department of Multi-Actor Systems, and Dr. Gonalo Correia from the department of Transport and Planning. I would like to thank everyone at the Delft University of Technology, Arcadis and the Municipality of The Hague who contributed in any way to this research. None of the parties involved have a conflict of interest when it comes to the publication of this article.

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