IET Intelligent Transport Systems

Special Issue: Selected Papers from the 25th ITS World Congress Copenhagen 2018

Simulating deployment of connectivity and automation on the Antwerp ring road

ISSN 1751-956X
Received on 26th January 2018
Revised 30th May 2018
Accepted on 18th July 2018
E-First on 24th September 2018
doi: 10.1049/iet-its.2018.5287
www.ietdl.org

Konstantinos Mattas[1,2], Michalis Makridis[1] ✉, Pauliana Hallac[3], María Alonso Raposo[1], Christian Thiel[1], Tomer Toledo[3], Biagio Ciuffo[1]

[1]Directorate for Energy, Transport and Climate, European Commission – Joint Research Centre, Via E. Fermi, 2749–21027 Ispra (VA), Italy
[2]Department of Civil Engineering, Democritus University of Thrace, Vasilissis Sofias 12, Xanthi 671 00, Greece
[3]Faculty of Civil and Environmental Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel
✉ *E-mail: Michail.MAKRIDIS@ec.europa.eu*

Abstract: As connectivity and automation make their way in to transportation systems, they are expected to have a forceful impact, drastically changing road transportation. The introduction of autonomous vehicles (AVs) and connected autonomous vehicles (CAVs) is expected to advance safety and comfort. But, they can also affect characteristics of road networks, such as capacities, delays and efficiency. To foresee important challenges, reinforce potential benefits and reduce potential disadvantages of this new disruptive technology, its impacts should be well studied and understood before their anticipated introduction. In this paper, a microscopic simulation framework to estimate these impacts is developed. Simulation experiments are conducted for various traffic mixtures of manually driven vehicles, AVs and CAVs, different desired time headways settings and traffic demand levels, to evaluate the sensitivity of the network performance to these factors. The ring road of Antwerp is used for the case study. Thus, the results and conclusions refer to a large real-world network. The consequences of the introduction of AVS and CAVs on traffic flow and pollutant emissions are evaluated. The results show that depending on the demand, AVs introduction can have negative effects on traffic flow, while CAVs may benefit the network performance, depending on their market penetration.

1 Introduction

Road transportation has a substantial impact on several areas. The environmental impacts of transport are substantial, especially since it is the only sector in Europe, where greenhouse gas emissions are still rising [1]. Mobility, the ability to transfer goods and people, is an important factor, affecting urban development and planning. Road safety is also a major issue, considering that there were more than 26,000 deaths in the EU alone in 2015. Technological advances in automation and connectivity are now promising to revolutionise the sector.

Low-level automation is already available for privately owned vehicles. Companies like Waymo [2] are promising to introduce fully autonomous vehicles (AVs) before long, for private ownership or considering mobility as a service. Connectivity can further increase the benefits of automation. Apart from safety and comfort, the introduction of AVs and connected AVs (CAVs) may, in the near future, have substantial effects on road networks, travel delay times, energy efficiency and traffic demand.

To foresee important challenges, reinforce potential benefits and, to the extent possible, prevent potential disadvantages of this new disruptive technology, its impacts should be well studied and understood before their anticipated introduction. Since large scale field experiments are currently next to impossible, simulation experiments are necessary. Taking into account the complexity of road transportation networks, these simulation experiments should be implemented on a large scale, realistic networks that closely represent existing networks and their characteristics.

The way that AVs and CAVs operate differs substantially from human driving. These differences should be represented in microscopic traffic simulation experiments. Their reaction time is expected to be lower than that of the average human driver, leading to safer and smoother traffic flows [3]. AVs are also expected to function in a safer and more conservative way, maintaining larger headways and avoiding the use of larger acceleration and deceleration that are outside the human comfort zone. CAVs, when they interact with other CAVs, can benefit from the information exchanged for a car following and lane changing, forming platoons that may increase lane capacities and for the network as a whole. Moreover, different cooperation and control strategies can be developed and exploited. To measure their effectiveness and necessity, a framework representing the base scenario is required.

The scope of this paper is to develop a microscopic traffic simulation framework to test the deployment of vehicles with automatic cruise control (ACC) and connected ACC (CACC) capabilities. This framework is utilised for a case study on the ring road of Antwerp. The network has been modelled in detail and the traffic demand has been estimated using observed peak period traffic counts. In the simulation experiment, the mix of vehicles with different technologies, their safety configurations and the level of traffic demand are varied. This produces a large number of scenarios that were tested. The behaviours of AVs and CAVs were modelled according to state of the art ACC and CACC algorithms, respectively. The COPERT (Computer Programme to calculate Emissions from Road Transport) emission model [4] is used to quantify the environmental effects on the network. The analysis of the results shows that ACC can have a negative impact on the network's congestion, depending on the market penetration rate and the desired time gap setting, which were assumed to be constant across vehicles. An interesting observation is that as the deployment of AVs approaches 100%, a capacity drop is observed on the network, which deteriorates traffic flow. This result shows the existence of trade-offs between the capabilities of the technology (shorter time gaps) and serving the goals of safety and comfort. CAVs can have slightly negative consequences on traffic flow in low penetration rates. With higher penetration rates, they are beneficial to the network performance, as long as traffic demand levels are not very high. The traffic demand level and the desired time gap for AVs had a substantial effect on the network's performance. The desired time gap choice seems to play an important role in critical situations where lane changes become mandatory. Thus, further research is recommended on cooperative control strategies that may support smoother lane changes for

CAVs. Regarding the environmental impacts, high penetration of AVs on high density roads seems to results in very high emission rates, while the high penetration rate of CAVs can prove to be beneficial.

The remaining of the paper is organised as follows: Section 2 presents the relevant literature on simulating AVs and CAVs. Section 3 describes the algorithms used for the simulation scenarios, major assumptions and limitations of the experiments. Section 4 provides the necessary information about the case study experiment and the simulation scenarios. Section 5 discusses the results of the simulation. Finally, conclusions and future work are presented in Section 6.

2 State-of-the-art

According to NHTSA [5], vehicle automation can be divided into five different categories referenced as levels of automation, from 0 to 4. Level of automation 0 is considered to be manual vehicles with no automated capabilities. Levels 1 and 2, incorporate function-specific automation and combined function automation, respectively. However, these are considered to provide driver assistance. Levels 3 and 4 vehicles can perform all driving functions, with the driver not expected to constantly monitor the roadway.

The highest automation level available in the market now is ACC systems, which correspond to level 2. CACC is another level 2 technology that is expected to become available in the market. It is currently subject to numerous experiments. Recent studies on the subject of vehicle automation and connectivity are listed in Table 1.

A substantial literature describing microscopic traffic simulation experiments of automation and connectivity exist. These studies use road sections or small networks, in some cases, with a limited number of on- and off-ramps. Experiments on larger networks, to the best of the authors' knowledge, are limited to macroscopic simulations. In [39] an evaluation of the impact of CACC on the Antwerp ring-road for different penetration rates and different traffic demands was presented. At that point, only cruising was performed by the CACC controller so that other manoeuvres where performed by the simulated human controller. The impact was beneficial for the network average speed and delay times. But, in some cases, the energy demand increased with the CACC market penetration rates because of the higher average speeds on the network. Also, a more detailed analysis of the work presented in Table 1 can be found in [39]. Another study [40] presented negative impacts of automation and connectivity, which may be caused by the coordination scheme that was utilised.

In the preparation for this new era of transportation, it is important to identify possible challenges before the introduction of fully functioning CAVs on our road networks. Hence, and because of the complexity of the transportation systems and the expensiveness of real experiments, simulation experiments on large networks are necessary. This is the objective of this paper, using what is considered by the authors to be the closest to a consensus on human driven and autonomous vehicle modelling.

Table 1 Literature review

Category	Studies
micro-simulation on simple networks	[3, 6–15]
overall assessment	[11, 16–21]
CACC behaviour model	[15, 18–29]
environmental impact	[22, 25, 28, 30–32]
macro-simulation experiments	[33–38]

Table 2 Vehicle parameters

Vehicle type	Max acceleration, m/s^2	Max deceleration, m/s^2	Reaction time, s
manual	4	−6	0.8
AV	2	−3	0.3
CAV	2	−3	0.3

3 Simulation set up

3.1 Assumptions and limitations

In order to model the behaviour of AVs and CAVs in microsimulation frameworks, various models with vastly different results have been presented on various studies mentioned in the state-of-the-art section [3, 6–15]. It has been assumed that the AVs and CAVs cruising behaviour can be simulated using models developed to describe ACC and CACC cruising controllers. Various different models have been proposed for ACC and CACC cruising, and the ones chosen represent models that have been broadly used and cited in studies in the field.

Regarding overtaking, lane changing and giving way behaviours, the default AIMSUN models have been used, taking into account the different reaction time and deceleration capabilities for AVs and CAVs. The assumption here is that the AVs will try to mimic human behaviour, according to their performance characteristics. The assumptions are considered to be valid, as the scope of this paper is not to introduce several optimal control algorithms targeted to various functionalities of CAVs, but to assess the possible impacts due to the introduction of connectivity and automation in a real network in order to highlight possible future challenges. The undesirable consequences that are presented are avoidable with appropriate legislation or coordination algorithms. Our goal is to identify those problems and estimate the most significant ones, to motivate further research.

3.2 Driver models

The AIMSUN traffic simulation model is used in this study. Three types of vehicles have to be simulated, to construct the mixture of the traffic that uses the network: manually driven cars with no automation capabilities, AVs were the human driver is not responsible to regain control at any point of the trip, and CAVs that operating as AVs and make use of their connectivity when possible. Details about vehicles lateral and longitudinal motion are presented in the following paragraphs.

Manual vehicles: For the simulation of manually driven vehicles, the default model that is implemented in AIMSUN was used. This is a modified Gipps' car-following model [41].

AVs without connectivity capability: To simulate AVs that do not have the ability to exchange information with other vehicles or the infrastructure, the model proposed in [3] was utilised. It is a first order model representing ACC vehicle longitudinal behaviour. For the lateral movement, the default AIMSUN model was used, according to the ACC maximum deceleration and car following deceleration functions. Also, AVs are forced to obey the speed limits, in contrast to manually driven vehicles that have an acceptance factor allowing them to accede to the speed limit.

Connected Automated vehicles: CAVs can be expected to have a car-following behaviour similar to CACC vehicles while cruising. Hence, the model described by Talebpour and Mahmassani [14] was used when following another CAV. The aforementioned AV model was used when following another type of vehicle, assuming that a CAV will behave as an AV when it is not able to exchange information with its neighbouring vehicles. CAVs are also forced to obey the speed limits, in the same way as AVs. Lane changing is again modelled based on the default AIMSUN algorithm, using the CAVs particular car following deceleration model.

Table 2 presents the values of the maximum acceleration and deceleration and reaction time parameters used with each model. The maximum parameter values reported in the table are used in AIMSUN as the means of normal distributions in the drivers' population. AVs and CAVs have more strict limits on accelerations and decelerations. These are aimed to increase passengers' comfort. Reaction times are also much lower for AVs and CAVs. But, they are not negligible. For other driving parameters, not shown in Table 2, the default values in AIMSUN were used for human-driven vehicles. Within the AV and CAV models, the

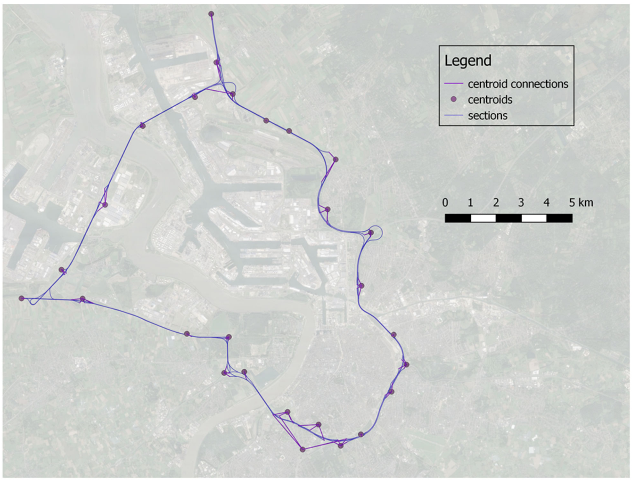

Fig. 1 *Antwerp and the ring road model*

Table 3 Mixture scenarios

		Penetration rate of CAVs					
		0%	20%	40%	60%	80%	100%
Penetration rate of AVs	0%	✓	✓	✓	✓	✓	✓
	20%	✓	✓	✓	✓	✓	
	40%	✓	✓	✓	✓		
	60%	✓	✓	✓			
	80%	✓	✓				
	100%	✓					

parameter values are those reported in the references they are derived from [3, 14].

3.3 Emission model

A point of concern for road transportation networks is the pollutants that road users' vehicles emit. It is suggested that the introduction of AVs and CAVs can have strong environmental effects [22, 25, 28, 30–32]. To test this it is necessary to estimate the emissions on a large network. These emissions depend on multiple variables and the use of an emission model is required.

COPERT and the Handbook of Emission Factors (HBFEFA) are the two reference emission models in Europe [4]. COPERT provides emission factors, functional relationships that predict the quantity of a pollutant that is emitted over distance. It has been shown that COPERT can estimate emissions on rural, urban or highway scenarios [42, 43]. The pollutants that are traced in the present paper are CO_2 and NOx emissions.

4 Case study

4.1 Antwerp's ring road

The case study network for the simulation experiments is the ring road around Antwerp, Belgium (Fig. 1). The ring road's specifications where extracted from OpenStreetMap and refined, resulting to a network consisting of 119 km of roads with 27 centroids (origin/destination points), 208 sections with variable numbers of lanes and 117 intersections. There are no traffic lights on the network. Due to the ring road shape, there are obvious paths for each O/D pair, so no distinction has been made between user equilibrium and system optimum, although this can amplify the benefits of connectivity in different situations.

Traffic count data during the morning peak hour, where utilised to produce the base scenario traffic demand. The Frank and Wolfe algorithm [44], which is available as a built in tool in AIMSUN was used to adjust a planning O/D matrix to the observed data. The OD objects of the network are 27 and the rush hour demand consists of 42,185 cars and 4899 heavy duty vehicles.

4.2 Scenarios

Three major factors have been identified, the level of traffic demand, the market shares of manual vehicles, AV and CAV, and the chosen time gap for the AVs when the car following. As the technology matures, the developers and users may gain confidence in it, and use lower headways in order to improve performance, while keeping a low crash risk.

To estimate the impact of automation on the roads, all these factors have been taken into account. For the mixture of vehicles, 21 different cases were studied, creating all possible combinations of market penetrations of each vehicle type ranging from 0 to 100% in intervals of 20% as shown in Table 3. Three different traffic demand cases, baseline, 80 and 120% of the baseline, and three different desired time gap size choices: 1.1, 1.6 and 2.2 s were used. In order to explore the entire space of the factors, the full factorial experiment was used. This results in 189 different scenarios that were tested. Each scenario was run for three hours with the second hour being the network's peak hour. The first and the last hours we loading and unloading periods with lower demand equal to 20% of the observed peak hour demand and the same proportions of the mix of vehicles.

5 Results

5.1 Set up and metrics

Data about the state of the network were gathered for intervals of 10 min. The data was not collected for the first 20 min, which was considered a warm up phase, to load the network with vehicles. As noted above, the demand increased to the peak hour value after the first hour of simulation, and then decreases again to the unloading phase demand after 2 h of simulation. Because of the magnitude of the network, the effects of the changes in the demand are observable after some delay, even in uncongested conditions. Therefore, data representing low demand refer to the interval from the 20th minute to the 80th. The peak hour is represented by the data from the 80th minute to the 140th.

The harmonic average speed for the whole network is used as an indicative metric for the traffic flow status. The harmonic average speed is calculated in km/h directly for every ten-minute

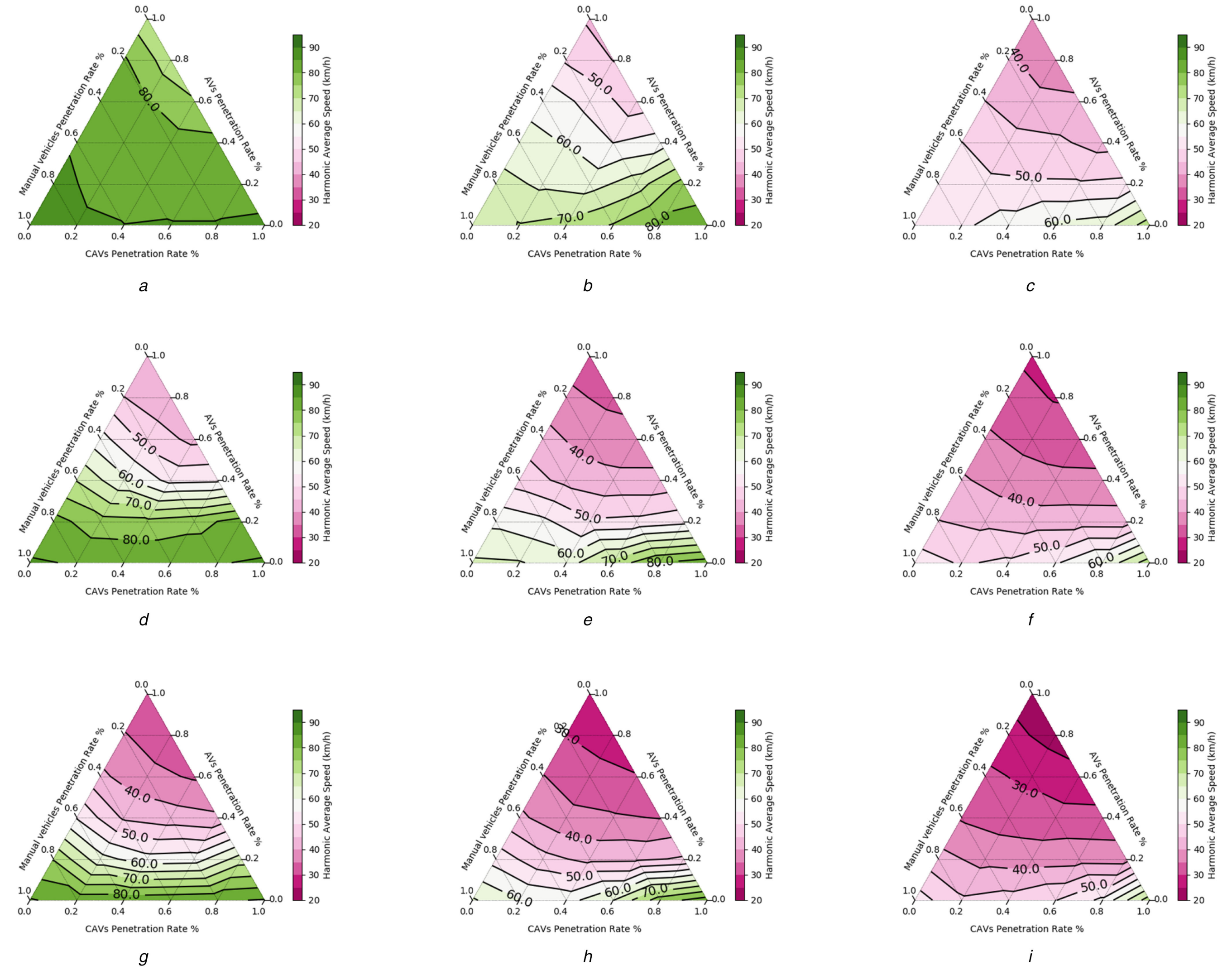

Fig. 2 *Harmonic speed of the network for the peak hour*
(a) Time gap 1.1 s and demand 80%, ***(b)*** Time gap 1.1 s and demand 100%, ***(c)*** Time gap 1.1 s and demand 120%, ***(d)*** Time gap 1.6 s and demand 80%, ***(e)*** Time gap 1.6 s and demand 100%, ***(f)*** Time gap 1.6 s and demand 120%, ***(g)*** Time gap 2.2 s and demand 80%, ***(h)*** Time gap 2.2 s and demand 100%, ***(i)*** Time gap 2.2 s and demand 120%

interval as the average space mean speed of all the vehicles. It is also useful to look at the density of vehicles in the network over time. The two metrics are closely related and so because of space limitations, the densities observed are not presented in detail.

5.2 Peak hour results

Fig. 2 presents the average harmonic speed for the peak hour demand in ternary plots for various demand levels and desired time gaps. In the figures, each corner represents the case of 100% penetration rate for the specific vehicle type. The space within the triangles represents different combinations of penetration rates of CAVs and AVs in the mixture of vehicles. At every point inside the triangle, the ratio of each vehicle type is in inverse proportion to the distance to its corner. The ternary plots are organised so that they have resulted by experiments with the same time gap for AVs with all in the same row, and the same traffic demand with all in the same column.

The first conclusion that can be drawn is that in every case the introduction of AVs can negatively affect the network's performance, even at low penetration rates. With AVs, headways on the network are larger since human drivers are willing to take risks and do not always keep the required gaps. In contrast, AVs always keep the minimum desired gaps.

An observation has also been made that the situation is much worse for AVs in bottlenecks when they have to merge or change lanes. The gap needed by an AV to perform a lane changing manoeuver is much larger than gaps accepted by human drivers since AVs have to maintain the required gaps, and their maximum deceleration is less than that of a manually driven vehicle, for safety and comfort reasons. Furthermore, maximum acceleration is smaller in AVs which is also an observation made in ACC vehicles that are available commercially. As a consequence, the flow downstream of a bottleneck is reduced, deteriorating the situation upstream. It should be noticed that the ACC model used in the simulations has also been tested for one section networks and the capacity was not much smaller than the default case. This is also a reason why it is suggested that the deterioration of the network's condition is because of the AVs inefficiency in lateral manoeuvres.

The results on the impact of the introduction of CAVs to the network depend on the CAVs penetration rate and the level of demand in the scenario. As mentioned earlier CAVs that follow AVs or manually driven vehicles react as AVs since they do not have any information from other vehicles to make use of their connectivity and cooperation functionalities. At low penetration rates, the probability of a CAV following another CAV to form a connected platoon is small. Therefore, most CAVs act as AVs, demanding larger headways to car-follow or lane change. As a result, at the small penetration of CAVs, and especially for the larger desired time gap scenarios, the average speed in the network decreases. However, with higher penetration of CAVs, gaps are smaller, lane changes are easier and the traffic streams are more stable and able to absorb oscillations without traffic breakdown occurring. Consequently, the harmonic average speed is higher, even for the scenarios with a high level of demand.

At low demand levels, manual vehicles can outperform CAVs because they are in free flow conditions and for the manually driven vehicles it is acceptable, and realistic not to abide by the speed limits. Finally, since for some situations CAVs behave as AVs, the value of the desired time gap has a significant effect on the results.

The ACC vehicles that are already on the market have different options for time gap choice by the driver. These time gaps are chosen in order for the passenger to feel safe and comfortable. The three different time gaps chosen for out simulations were proposed in [3] and are representative of the values decided by real drivers who took part in experiments. With the introduction of automation time gaps are expected to be large, but as the technology matures, and the public becomes more aware and familiar with it, it is possible that time gaps can be set lower to values that are closer to those that are indeed needed for the passengers' safety. The results from the simulations show a very large influence of the desired time gap in the networks' performance. Comparing Figs. 2*c* and *e* or Figs. 2*b* and *d*, it can be deduced that the time gap choice is almost as influential as the level of traffic demand. The larger value of 2.2 s time gap is by far the most impactful on the network, as even for the lower demand scenarios, the averages speeds calculated are lower than the averages speeds for 1.1 s headways for 100% AVs. The increase in the market penetration of CAVs that is required in order to compensate for the effect of the large time gap is around 60% when there are no AVs on the network. Thus, with higher penetration rates CAVs can be beneficial, but with lower penetration rates and large chosen headways, and with high demand levels, the average speed on the network drops drastically. For completeness, Fig. 3 shows the density results for a representative case, with 1.6 s time gap and 100% demand that further supports the derived conclusions.

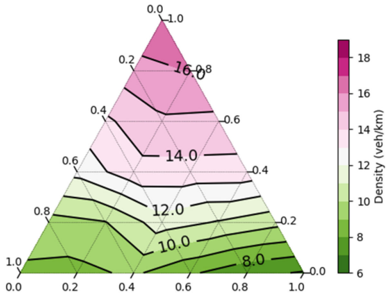

Fig. 3 *Representative density for time gap 1.6 s and demand 100%*

5.3 Loading phase

Fig. 4 shows the harmonic speeds in the network for 1 h of low demand (from minute 20th–80th). During most of this time, the traffic demand into the network is low. In the last 20 the demand increases to the peak hour level, but due to the spatial extent, the effect on the flow is not yet observed. Overall, the performance with AVs in the traffic stream is again worse than with manual vehicles or CAVs. For example, in the case of set gap of 1.1 s and 100% demand level (Fig. 2*b*) the average speed is 44.2 km/h for 100% share of AVs, 82.6 km/h for 100% share of CAVs and 65.6 km/h for human-driven vehicles. However, in this case, the time gap is more significant as a factor than the level of demand, which is low in all cases until the last 20 min of the interval. For example,

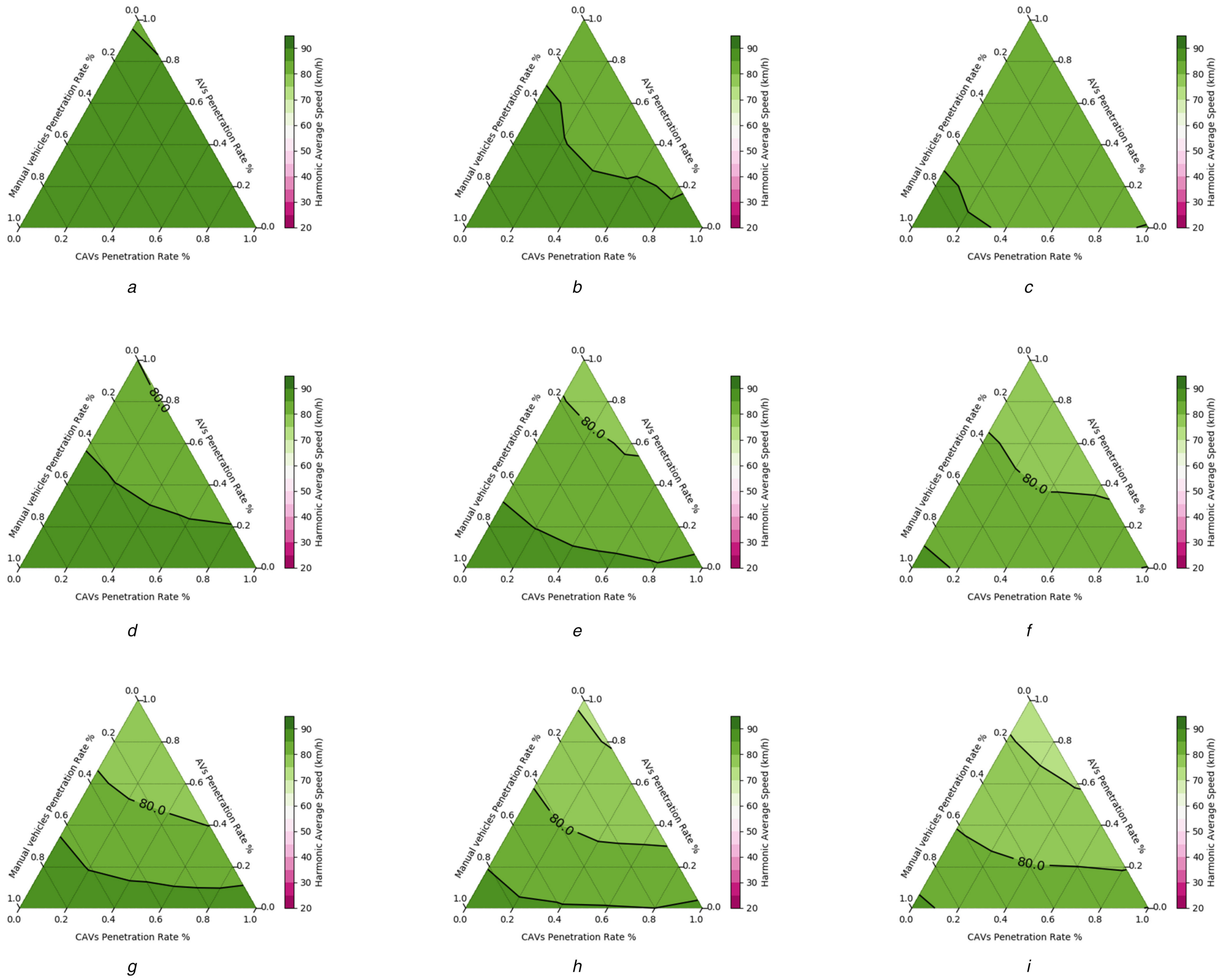

Fig. 4 *Harmonic speed of the network for the low demand*
(a) Time gap 1.1 s and demand 80%, ***(b)*** Time gap 1.1 s and demand 100%, ***(c)*** Time gap 1.1 s and demand 120%, ***(d)*** Time gap 1.6 s and demand 80%, ***(e)*** Time gap 1.6 s and demand 100%, ***(f)*** Time gap 1.6 s and demand 120%, ***(g)*** Time gap 2.2 s and demand 80%, ***(h)*** Time gap 2.2 s and demand 100%, ***(i)*** time gap 2.2 s and demand 120%

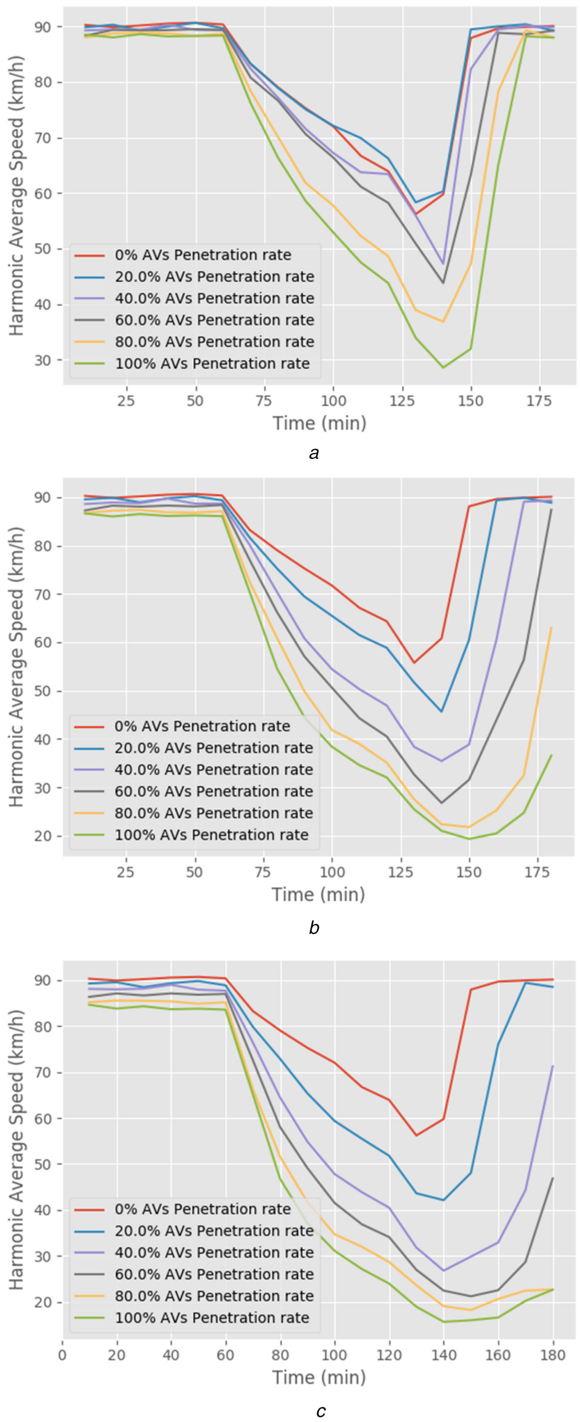

Fig. 5 *Harmonic speed of the network for base demand and various AVs penetration rates*
(a) Time gap 1.1 s, ***(b)*** Time gap 1.6 s, ***(c)*** Time gap 2.2 s

for a 100% share of AVs, the average speed with a set gap of 1.6 s is lower than that with a set gap of 1.1 s even when the former is simulated with the lowest 80% demand level (Fig. 2*d*) and the latter with the highest 120% demand (Fig. 2*c*).

The effect of the addition of CAVs to the traffic mix on the harmonic speed is slightly negative. Human-driven vehicles have the advantage on this metric as a consequence of their capability to travel at speeds that are higher than the speed limit. Furthermore, these vehicles are also able to accelerate harder, while CAVs are limited to the comfortable acceleration range.

Summarising the results, a concern arises regarding the intermediate effect of automation. It is projected that the move to fully automated, connected and coordinated road transport will be a matter of decades [45]. Once the transition is completed, it is assumed that travel demand will increase from current levels. Users that cannot drive a vehicle will have full access to the network. Central or local controllers utilising the connectivity capabilities can reroute traffic, manage bottlenecks and control lane changing and merging. They, therefore, may increase the capacity of road networks further than estimated by the present study. However, the results reported here indicate that the benefits of connectivity to traffic flow may not be realised until a high market share is obtained. Furthermore, connectivity adds security risks to the system. Communications may break down due to security reasons, malevolent attacks, technology failures or natural incidents. In these cases, it is possible that many of the users of the network will not be able to drive their vehicles but move to AV driving. This is likely to have detrimental effects on traffic flow. As a worst-case scenario, in the case study results, turning from 100% CAVs to 100% AVs in a network with high demand may cause the average speed to drop from 72.8 to <22.6 km/h.

5.4 Speed over time

Fig. 5 shows the time series of the harmonic average speed for various penetration rates of AVs and for the three different time gap options. The figures assume that other vehicles are all human-driven. With short set time gaps and low AV penetration rates, the negative impacts are relatively small. For a 20% penetration rate, the harmonic speed even slightly increases over the base scenario. However, as the penetration rate of AVs increases, the impact on speed becomes negative and more pronounced. In all cases, the speed is lowest with the 100% AVs penetration rate. Furthermore, the time period in which speeds are negatively affected is also longer when the share of AVs is larger. With no AVs, the speed is restored to free flow conditions 30 min after the peak demand period ends. But, with 100% AVs, this takes about 50 min. Similarly, the drop in the speed at the beginning of the peak demand period is steeper with the higher AVs penetration rates.

The figure also shows the sensitivity of travel speeds to the desired gap settings. At low levels of traffic demands, the difference is not substantial. But, once the demand increases to its peak hour level, the differences are clearly visible. The longer set time gaps yield lower speeds. For example, for the case of 100% share of AVs, the lowest speeds observed are 28.6, 21 and 15.6 km/h, for set time gaps of 1.1, 1.6 and 2.2 s, respectively. Longer time gaps are expected to be preferred from a safety point of view. Therefore, the results suggest that varying time gaps, depending on the traffic conditions, with shorter set gaps in congested sections and longer set gaps for less congested parts of the trip may be useful.

The corresponding results for CAVs penetration rates are presented in Fig. 6. At high penetration rates, the results do not depend on the set time gap. Most vehicles travel in platoons of CAVs that can dampen oscillations and assist the flow at bottlenecks. At low penetration rates, the CAVs are not able to fully utilise the connectivity as there are not many other CAVs on the network that they can communicate with. As a result, they mostly operate in the same way as AVs, and negatively affect travel speeds. For the longer set time gaps, in Figs. 6*b* and *c*, the speed is lower with low penetration rates of CAVs, compared to the case that they are not present in the vehicle mix. For the largest set time gap, the speed improves over the case of only human-driven vehicles only after the share of CAVs reaches 60%. In contrast, for the shorter set time gap shown in Fig. 6*a*, the introduction of CAVs in the network is always beneficial to travel speeds, even with the lowest penetration rate of 20%. It should also be noted that the results are dependent on the data items that are communicated between vehicles and the quality of the control algorithms that manage the cooperation between vehicles. Better control and communications may allow better results both at all levels of penetration rates. However, reviewing control algorithms and testing them is outside the scope of this paper.

5.5 Environmental impacts

Regarding the pollutant emissions, the results for time gap 1.6 s are presented in Fig. 7 in the form of ternary plots. At the lower level of traffic demand, the most emissions per kilometre measured in

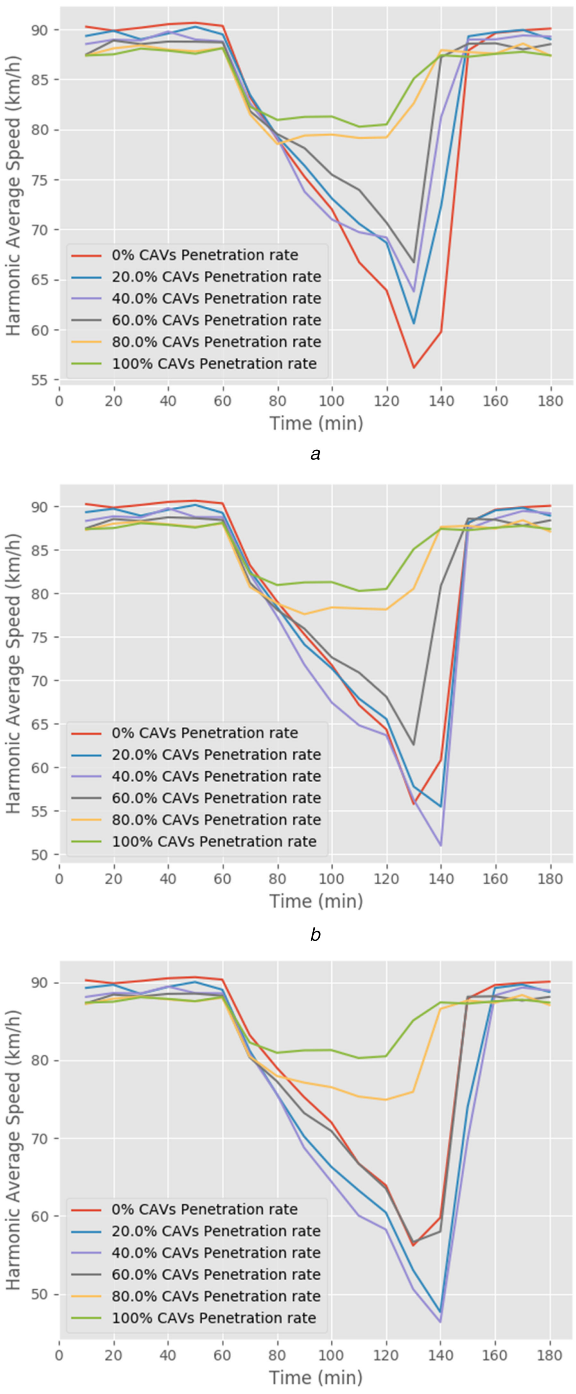

Fig. 6 *Harmonic speed of the network for base demand and various CAVs penetration rates*
(a) Time gap 1.1 s, ***(b)*** Time gap 1.6 s, ***(c)*** Time gap 2.2 s

the case that all vehicles are human-driven. With the higher demand levels, the introduction of AVs in the vehicle mix, especially at high penetration rates, increases emissions. In contrast, CAVs seem to decrease emissions. These findings can be explained by the average speed on the network presented in Fig. 2. For all the internal combustion engines, the quantity of emissions is strongly correlated to the speed. There is an optimal interval that is different for each type of engine and vehicle, and both lower and higher speeds seem to emit bigger amounts of pollutants per kilometre. This optimum interval for the presented scenario seems to be for average speed around 60–70 km/h. At low traffic demand, AVs and CAVs are bound to the speed limits, while human drivers are not. Therefore, the latter pollutes more. In that light, it is possible that automation can help increase the efficiency and lower pollutant emissions if connectivity is utilised and the deterioration of traffic flow because of AVs will be avoided.

6 Conclusions

This paper presents a simulation-based impact assessment, on a realistic traffic network, of the anticipated introduction of autonomous and connected automated vehicles. The case study uses the ring road of Antwerp, a city in Belgium with the second largest European port. A base travel demand for this network was estimated from traffic count data. The state-of-the-art car following models specifically developed for AVs and CAVs were used in the simulation model. Lane changing behaviour was assumed to be similar to that of human drivers, but using the acceleration and reaction time characteristics of AVs and CAVs. The default models implemented in the AIMSUN traffic simulation software were used.

Different scenarios were defined and tested to account for the impact of various mixtures of human-driven vehicles, AVs and CAVs. Moreover, the tests were carried out for three different traffic demands, 80, 100 and 120% of the base scenario, and for three different desired time gaps for the AVs, 1.1, 1.6 and 2.2 s. The resulting experimental design included a total of 189 scenarios.

The results concerning AVs showed that they can have a negative effect on traffic speeds. With high penetration rates of AVs, the average speed on the network decreases, while the density increases. The desired time gap of the AVs proved to be having a substantial influence on the results, in some cases more than the traffic demand. These negative effects are attributed to the more conservative driving of AVs compared to human drivers in acceleration behaviour, but also in lateral movement, which is affected by the acceleration bounds and speed limit. As a result, AVs require larger gaps in order to lane change, they are forced to decelerate more until they find an appropriate gap and therefore cause delays to the traffic flow. At low levels of demand, vehicles are moving at high speeds and the influence of the set time gap is small. These results suggest that variable set time gaps that depend on the traffic state: longer set time gaps can provide high levels of safety at higher speeds. Shorter set time gap can support better traffic speeds in dens traffic and at bottlenecks.

The introduction of CAVs to the vehicle mix proved to be beneficial to travel speeds in some cases. At low penetration rates, CAVs have small negative effects. In this case, they mostly act as AVs since there are not many vehicles to exchange information with. At the lower levels of traffic demands, human-driven vehicles outperformed CAVs even on higher penetration rates due to the strict observation of acceleration bounds and speed limits by CAVs. However, with higher levels of demand and high CAVs penetration rates, they were able to create platoons, dampen oscillations and as results, support higher average speeds in the network.

Automation and connectivity can be used together with various optimisation algorithms to control the traffic and further enhance the benefits to the network. Introduction of dedicated lanes for these vehicles could also reduce the negative effects of their presence on traffic flow. These strategies were not used in this paper as the goal of the study was to screen the base scenarios and identify the potential challenges and benefits. An important challenge that emerges from the results is the need for smooth lane changing and overtaking algorithms for AVs and CAVs.

Another important remark relates to the results that shows the substantial advantage of CAVs over AVs in terms of traffic flow. It suggests the importance of maintaining connectivity. In a fully connected and automated environment, safety reasons, attacks, communication failures and other reasons may interrupt connectivity. This may cause CAVs to behave as AVs, which based on the results may deteriorate traffic speeds significantly. Thus, further research is advocated on optimal control of AVs and on security and safety issues regarding CAVs.

The environmental impacts that have been studied where CO_2 and NOx emissions per kilometre. In free flow conditions, human drivers that are not bounded by the speed limits as strictly as AVs

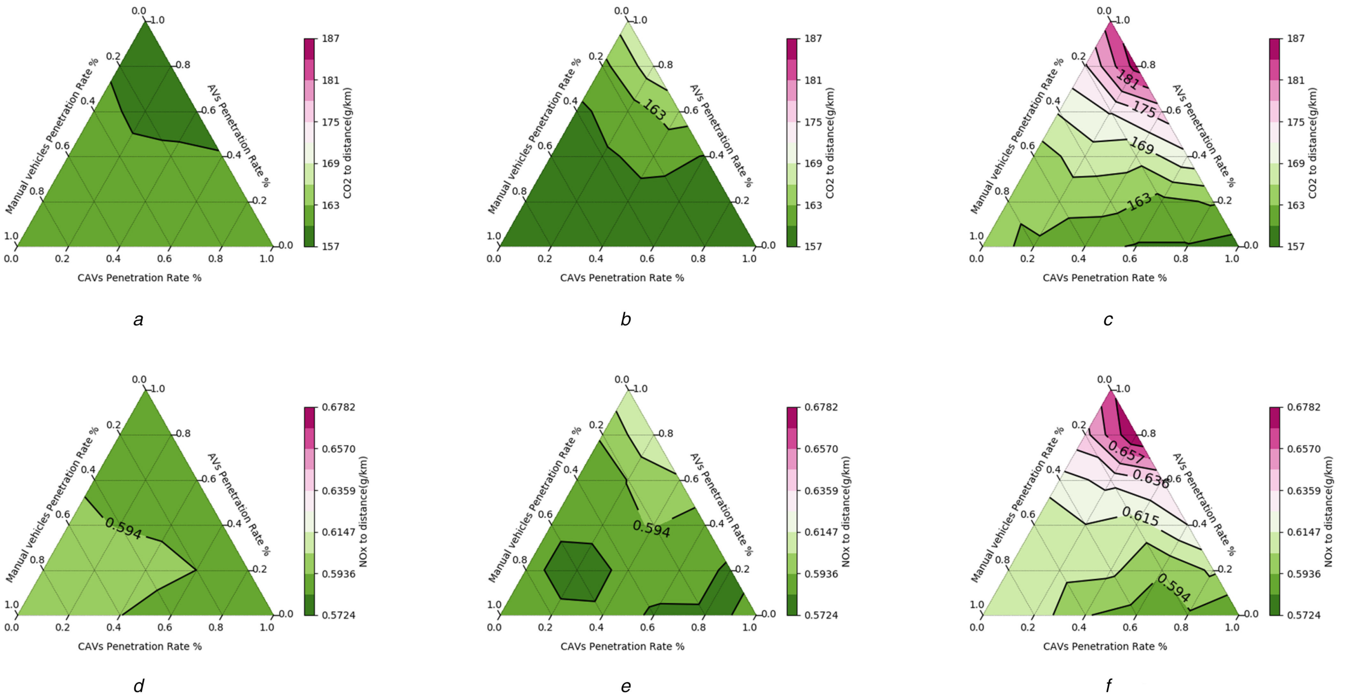

Fig. 7 *Pollutant emissions calculated for time gap 1.6 s*
(a) CO_2 per kilometre for demand 80%, ***(b)*** CO_2 per kilometre for demand 100%, ***(c)*** CO_2 per kilometre for demand 120%, ***(d)*** NOx per kilometre for demand 80%, ***(e)*** NOx per kilometre for demand 100%, ***(f)*** NOx per kilometre for demand 120%

and CAVs produced the poorest results. High CAVs penetration rates yielded lower emissions in all cases. In contrast, AVs reduced traffic speeds and so forced the engines to work in less efficient spaces. Thus, they increased emissions. For AVs, this strengthens the argument that they should not use internal combustion engines. However, it should be noted that their introduction also affects the speeds of other vehicles, and so some of the negative impacts on emissions would not be eliminated.

Future research will focus on the opportunities introduced by a coordination at the system, segment or network level to better manage the movements of vehicles in order to achieve system optima in terms of multiple objectives: travel times, energy consumption and emissions.

7 Acknowledgments

Hallac and Toledo were sponsored in part by a grant from the Israeli Ministry of National Infrastructure, Energy and Water Resources.

8 References

[1] European Commission: 'White paper 2011 – mobility and transport – European commission', Mobility and Transport. Available at http://www.transport/themes/strategies/2011_white_paper_en, Accessed 18 May 2017

[2] Gibbs, S.: 'Google sibling waymo launches fully autonomous ride-hailing service', The Guardian, 07 November 2017

[3] Shladover, S., Su, D., Lu, X.-Y.: 'Impacts of cooperative adaptive cruise control on freeway traffic flow', *Transp. Res. Rec. J. Transp. Res. Board*, 2012, **2324**, pp. 63–70

[4] Ntziachristos, L., Samaras, Z.: 'EMEP/EEA air pollutant emission inventory guidebook – 2009', vol. Part B: sectoral guidance chapters, 1. Energy. 1.A Combustion. 1.A.3.b.i, 1.A.3.b.ii, 1.A.3.b.iii, 1.A.3.b.iv. Passenger cars, light-duty trucks, heavy-vehicles including buses and motorcycles, European Environment Agency, 2009, pp. 1–121

[5] National Highway Traffic Safety Administration: 'Preliminary statement of policy concerning automated vehicles', 2013

[6] van Arem, B., van Driel, C.J.G., Visser, R.: 'The impact of cooperative adaptive cruise control on traffic-flow characteristics', *IEEE Trans. Intell. Transp. Syst.*, 2006, **7**, (4), pp. 429–436

[7] Arnaout, G.M., Bowling, S.: 'A progressive deployment strategy for cooperative adaptive cruise control to improve traffic dynamics', *Int. J. Autom. Comput.*, 2014, **11**, (1), pp. 10–18

[8] Bang, S., Ahn, S.: 'Platooning strategy for connected and autonomous vehicles: transition from light traffic'. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, Washington, DC, USA, 2017

[9] Calvert, S.C., van den Broek, T.H.A., van Noort, M.: 'Cooperative driving in mixed traffic networks #x2014; optimizing for performance'. 2012 IEEE Intelligent Vehicles Symp., Alcala de Henares, Spain, 2012, pp. 861–866

[10] Calvert, S.C., van den Broek, T.H.A., van Noort, M.: 'Modelling cooperative driving in congestion shockwaves on a freeway network'. 2011 14th Int. IEEE Conf. on Intelligent Transportation Systems (ITSC), Washington, DC, USA, 2011, pp. 614–619

[11] Chen, D., Ahn, S., Chitturi, M., *et al.*: 'Towards vehicle automation: roadway capacity formulation for traffic mixed with regular and automated vehicles', *Transp. Res. B Methodol.*, 2017, **100**, pp. 196–221

[12] Guériau, M., Billot, R., El Faouzi, N.-E., *et al.*: 'How to assess the benefits of connected vehicles? A simulation framework for the design of cooperative traffic management strategies', *Transp. Res. C Emerg. Technol.*, 2016, **67**, pp. 266–279

[13] Milanés, V., Shladover, S.E., Spring, J., *et al.*: 'Cooperative adaptive cruise control in real traffic situations', *IEEE Trans. Intell. Transp. Syst.*, 2014, **15**, (1), pp. 296–305

[14] Talebpour, A., Mahmassani, H.S.: 'Influence of connected and autonomous vehicles on traffic flow stability and throughput', *Transp. Res. C Emerg. Technol.*, 2016, **71**, pp. 143–163

[15] Wang, C., Nijmeijer, H.: 'String stable heterogeneous vehicle platoon using cooperative adaptive cruise control', 2015, pp. 1977–1982

[16] Becker, F., Axhausen, K.W.: 'Literature review on surveys investigating the acceptance of autonomous vehicles'. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, Washington, DC, USA, 2017

[17] Diakaki, C., Papageorgiou, M., Papamichail, I., *et al.*: 'Overview and analysis of vehicle automation and communication systems from a motorway traffic management perspective', *Transp. Res. Part Policy Pract.*, 2015, **75**, pp. 147–165

[18] Fagnant, D.J., Kockelman, K.: 'Preparing a nation for autonomous vehicles: opportunities, barriers and policy recommendations', *Transp. Res. Part Policy Pract.*, 2015, **77**, pp. 167–181

[19] Farah, H., Koutsopoulos, H.N.: 'Impact of cooperative systems on drivers' car-following behavior'. Presented at the Transportation Research Board 91st Annual Meeting Transportation Research Board, Washington, DC, USA, 2012

[20] Jadaan, K., Zeater, S., Abukhalil, Y.: 'Connected vehicles: an innovative transport technology', *Procedia Eng.*, 2017, **187**, pp. 641–648

[21] Litman, T.: 'Autonomous vehicle implementation predictions: implications for transport planning'. Presented at the Transportation Research Board 94th Annual Meeting Transportation Research Board, Washington, DC, USA, 2015

[22] Akhegaonkar, S., Nouveliere, L., Glaser, S., *et al.*: 'Smart and green ACC: energy and safety optimization strategies for EVs', *IEEE Trans. Syst. Man Cybern. Syst.*, 2016, **48**, pp. 1–12

[23] Cao, P., Hu, Y., Miwa, T., *et al.*: 'An optimal mandatory lane change decision model for autonomous vehicles in urban arterials', *J. Intell. Transp. Syst.*, 2017, **21**, pp. 1–14

[24] Chin, H., Okuda, H., Tazaki, Y., *et al.*: 'Model predictive cooperative cruise control in mixed traffic'. IECON 2015 – 41st Annual Conf. of the IEEE Industrial Electronics Society, Yokohama, JP, 2015, pp. 003199–003205

[25] Gáspár, P., Németh, B.: 'Design of adaptive cruise control for road vehicles using topographic and traffic information', *IFAC Proc. Vol.*, 2014, **47**, (3), pp. 4184–4189

[26] Li, L., Ma, W.: 'A collision-free car-following model for connected automated vehicles'. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, Washington, DC, USA, 2017
[27] Lu, X.-Y., (David) Kan, X., Shladover, S.E., *et al.*: 'An enhanced microscopic traffic simulation model for application to connected automated vehicles'. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, Washington, DC, USA, 2017
[28] Qi, X., Wu, G., Hao, P., *et al.*: 'Integrated-connected eco-driving system for PHEVs with co-optimization of vehicle dynamics and powertrain operations', *IEEE Trans. Intell. Veh.*, 2017, **2**, (1), pp. 2–13
[29] Rahman, M., Chowdhury, M., Dey, K., *et al.*: 'An evaluation strategy for driver car-following behavior models for CACC controllers'. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, Washington, DC, USA, 2017
[30] Barth, M., Boriboonsomsin, K., Wu, G.: 'The potential role of vehicle automation in reducing traffic-related energy and emissions'. 2013 Int. Conf. on Connected Vehicles and Expo (ICCVE), Las Vegas, Nevada, USA, 2013, pp. 604–605
[31] Khondaker, B., Kattan, L.: 'Variable speed limit: a microscopic analysis in a connected vehicle environment', *Transp. Res. C Emerg. Technol.*, 2015, **58**, pp. 146–159
[32] Wang, M., Daamen, W., Hoogendoorn, S., *et al.*: 'Investigating potential impacts of an optimization-based Eco-ACC system on traffic and environment'. Presented at the Transportation Research Board 91st Annual Meeting Transportation Research Board, Washington, DC, USA, 2012
[33] Davis, L.C.: 'Dynamic origin-to-destination routing of wirelessly connected, autonomous vehicles on a congested network', *Phys. Stat. Mech. Appl.*, 2017, **478**, pp. 93–102
[34] Delis, A.I., Nikolos, I.K., Papageorgiou, M.: 'Simulation of the penetration rate effects of ACC and CACC on macroscopic traffic dynamics'. 2016 IEEE 19th Int. Conf. on Intelligent Transportation Systems (ITSC), Rio de Janeiro, Brazil, 2016, pp. 336–341
[35] Fakharian Qom, S., Xiao, Y., Hadi, M.: 'Evaluation of cooperative adaptive cruise control (CACC) vehicles on managed lanes utilizing macroscopic and mesoscopic simulation'. Presented at the Transportation Research Board 95th Annual Meeting Transportation Research Board, Washington, DC, USA, 2016
[36] Kloostra, B., Roorda, M.J.: 'Fully autonomous vehicles: analyzing transportation network performance and operating scenarios in the greater Toronto area, Canada'. Presented at the Transportation Research Board 96th Annual Meeting Transportation Research Board, Washington, DC, USA, 2017
[37] Ngoduy, D.: 'Instability of cooperative adaptive cruise control traffic flow: a macroscopic approach', *Commun. Nonlinear Sci. Numer. Simul.*, 2013, **18**, (10), pp. 2838–2851
[38] Patel, R., Levin, M.W., Boyles, S.D.: 'Effects of autonomous vehicle behavior on arterial and freeway networks', *Transp. Res. Rec. J. Transp. Res. Board*, 2016, **2561**
[39] Makridis, M., Mattas, K., Ciuffo, B., *et al.*: 'Assessing the impact of connected and automated vehicles. a freeway scenario'. Advanced Microsystems for Automotive Applications 2017, Cham, 2018, pp. 213–225
[40] Shelton, J.A., T. A. & M. T. I. T. P. R. Center: '*Revolutionizing our roadways: modeling the traffic impacts from automated and connected vehicles in a complex, congested urban setting*' (Texas A & M Transportation Institute, 2016)
[41] Gipps, P.G.: 'A behavioural car-following model for computer simulation', *Transp. Res. B Methodol.*, 1981, **15**, (2), pp. 105–111
[42] Fontaras, G., Franco, V., Dilara, P., *et al.*: 'Development and review of euro 5 passenger car emission factors based on experimental results over various driving cycles', *Sci. Total Environ.*, 2014, **468–469**, pp. 1034–1042
[43] Kousoulidou, M., Fontaras, G., Ntziachristos, L., *et al.*: 'Use of portable emissions measurement system (PEMS) for the development and validation of passenger car emission factors', *Atmos. Environ.*, 2013, **64**, pp. 329–338
[44] Frank, M., Wolfe, P.: 'An algorithm for quadratic programming', *Nav. Res. Logist. Q*, 1956, **3**, (1–2), pp. 95–110
[45] Alonso Raposo, M., Ciuffo, B., Makridis, M., *et al.*: 'The r-evolution of driving: from connected vehicles to coordinated automated road transport (C-ART)', Eur. Commun., 2017