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Connected and Automated Vehicles on a freeway scenario. Effect on traffic congestion and network capacity

Michail Makridis^a, Konstantinos Mattas^a, Biagio Ciuffo^{a,*}, Maria Alonso Raposo^a,
Tomer Toledo^b, Christian Thiel^a

^aDirectorate for Energy, Transport and Climate, European Commission – Joint Research Centre, Via E. Fermi, 2749 – 21027 Ispra (VA), Italy

^b Faculty of Civil and Environmental Engineering, Transportation Research Institute, Technion - Israel Institute of Technology, 711 Rabin Bldg., Haifa 32000, Israel

Abstract

In the next decades, road transport will undergo a deep transformation with the advent of Connected and Automated Vehicles (CAVs), which are about to drastically change the way we commute. CAVs promise to increase productivity and comfort and to facilitate a greater inclusion in mobility of specific user groups, which may eventually lead to increased travel demand. Together, CAVs will enable the full potential of self-driving technology and they will completely merge over time. The complexity of transportation systems is high and therefore, efficient tools for the assessment of this disruptive change are important.

The objective of this paper is to evaluate the behavior of automation and/or connectivity in vehicles under realistic traffic conditions and provide preliminary indicative results aiming to assess the efficiency of the corresponding technologies in terms of traffic congestions and network capacity. In the present work, the case-study of the ring road of Antwerp was used along with traffic demand generated based on real traffic counts.

Preliminary results show that, *ceteris paribus*, automation alone is less probable to have positive impacts on traffic conditions. The safety constraints that AVs will be designed to fulfill are in fact likely to generate vehicle which are as cautious (if not more cautious), than human drivers. In this picture, the significant step ahead can be brought by connectivity. Vehicles able to communicate in a seamless and secure way can theoretically see an effective reduction in time headways and reaction time with a consequent positive effect on network capacity and thus road congestion until the traffic demand stays constant. This effect is made more evident as their penetration rate over the entire network increases.

Preliminary results presented in this paper seem to confirm the effectiveness of the strategy put forward by the European Commission to consider connectivity, cooperation and automation as deeply intertwined aspects of the future transformation in the transportation sector.

Keywords: Connected and Automated Vehicles (CAVs), Platooning, Traffic simulation, Traffic flow

* Corresponding author. Tel.: +39.0332.789732; fax: +39. 0332.786627E-mail address: biagio.ciuffo@ec.europa.eu

1. Introduction

Embedding connectivity and automation to vehicles gives new unprecedented capabilities in comparison with the way we travel today, especially if this technological advance is combined with higher layer coordination among vehicles with similar or compatible capabilities. (Shladover et al., 2015). Among many others, anticipated benefits include increased safety, improved traffic conditions, greater efficiency in terms of fuel/energy consumption, and lower emissions. The generation of real or nearly-real time data could enable new possibilities in terms of traffic management. On the other hand, it is difficult to estimate impacts related to potential increases in travel demand. Privacy and security challenges can emerge with the connectivity and coordination of vehicles (Fagnant and Kockelman, 2015; Jadaan et al., 2017; Litman, 2015). It is expected that over the next 30 years CAVs will heavily impact the current transport networks. This might ultimately result in completely reshaping the road transportation from what it is today (Alonso Raposo et al., to be published). Therefore, it is apparent that new tools should be developed for studying, assessing and predicting the impact of connectivity and automation technologies on transportation. Many recent publications deal with the consumer acceptance of these new technologies (Becker and Axhausen, 2017), or with the behavioral changes of drivers that are using automated features (Farah and Koutsopoulos, 2012). Experiments involving the use of CAVs are also carried out to validate the performance of newly developed controllers and their improvements with respect to the current technology. (Milanés et al., 2014). The complexity of transportation systems is high and therefore the development of the appropriate assessment tools is important. As the deployment of the CAV technology is still in an early state, first assessments need to largely rely on simulation tools and scenarios that can extrapolate local behaviours and present estimations on potential impacts on a large scale.

Cooperative adaptive cruise control (CACC) and adaptive cruise control (ACC) are currently considered important technologies in the first stages towards autonomous driving and can demonstrate how automation can impact transportation systems, especially in freeway scenarios. In such scenarios, ACC and CACC logic can be used to simulate the cursing behaviour of AVs and CAVs respectively.

The results presented in this work focus on highway transportation where AVs and CAVs will coexist with manually driven vehicles and road transportation demand is expected to rise with the introduction of automation and connectivity (Alonso Raposo et al., to be published). Based on the above, the simulation scenarios included in this paper focus on variable mixtures of AVs, CAVs and conventional vehicle and variable travel demands. The case study for the present work is the ring road of Antwerp, a city with a population of over half a million built around the second biggest European port. The ring-road is therefore used to connect the port to the European motorway network. As a result the ring-road is heavy congested especially during the peak hours and is responsible for almost 50% of the traffic and road transport pollution of Antwerp (Lefebvre et al., 2011, 2013; Degraeuwe et al., 2016, p. 2). The simulations are carried out using the Aimsun commercial simulation software.

The rest of the paper is organized as follows: Section 2 presents the relevant literature on simulating AVs and CAVs. Section 3 describes the network, data and algorithms used for the simulation scenarios. Section 4 discusses the results of the simulation. Finally, conclusions and future work are presented in Section 5.

2. Related work

Autonomous vehicles are not yet available in the market, but in the literature there is a great interest over their potential impact in future transport networks. Currently there are various studies (Arbib and Seba, 2017; "Connected and autonomous vehicles," 2017; Milakis et al., 2017) trying to forecast market penetration of AVs and connectivity in the short-term (i.e. 2030) or long-term (i.e. 2050) based on social, economic, technology related factors. On the same time, in the recent literature there are several studies focusing on the impact of CACC and ACC technologies, which can be considered as the automation and connectivity in its infancy. There are several works in the literature describing the above-mentioned technologies. Gaspar et al. (Gáspár and Németh, 2014) proposed an optimization algorithm utilizing topological and traffic condition data received via Vehicle-to-Vehicle (V2V) or Infrastructure-to-Vehicle (I2V) communications, attempting to minimize fuel consumption while not deteriorating the traffic condition. Another model named PrARX has been proposed by Chin et al. (Chin et al., 2015). It has the ability to probabilistically predict the behavior of human drivers and adjust the CACC behavior according to the prediction (Chin et al., 2015). Xiao et al. developed and tested with micro simulation a model that extends empirical models with a human intervention regime (Xiao et al., 2017). According to Li and Ma (Li and Ma, 2017), the first parameter that should be optimized is safety and not string stability, flow or efficiency. Accordingly, they developed their CACC controller prioritizing safety. In particular they simulated a

string of 8 vehicles for different scenarios, proving that it is collision free under all circumstances of hard braking, it has good string stability and it is efficient. Other models have been proposed and tested in micro simulations (Lu et al., 2017; Rahman et al., 2017; Tiganasu et al., 2016), with Lu et al. simulating a 13 mile long freeway in Sacramento using real data, and showcasing the ability of the model to represent the present fleet, but without presenting results for CACC fleet or for mixed traffic. Finally Cao et al. (Cao et al., 2017) proposed an algorithm that can also perform mandatory lane changes using an optimization algorithm.

Connected vehicles can travel and exchange information, so their reaction time can be much shorter than that of human drivers and the required headways can be much smaller. Small distances between traveling vehicles result in increasing the capacity of a lane and this is considered an important advantage of CAVs (Makridis et al., 2018). This has been showcased by many researchers using simulations and/or theoretical analysis. Van Arem et al. (Arem et al., 2006) used MIXIC to simulate an existing highway with a lane drop from 4 to 3 lanes and observed the flow and capacity improvements due to CACC. Shladover et al. (Shladover et al., 2012) simulated a synthetic highway scenario (6.5km with no ramps and intersections) using realistic headway choices derived from stated preference surveys. They concluded that CACC can help with congestion but ACC without coordination is not very promising. More simulations have been run on realistic data from sections of freeways in the Netherlands for different penetration rates (Calvert et al., 2011, 2012). Also strategies have been tested using HOV lanes, that proved beneficial for small market penetration rates (Arnaout and Bowling, 2014). Milanés et al. (Milanés et al., 2014) experiment using real cars with CACC controllers is noteworthy because the capacity gain and the string stability in a connected and automated environment has been demonstrated. Furthermore, string stability has been evaluated for heterogeneous platoons and the impact of the parameters to the string stability has been assessed (Wang and Nijmeijer, 2015). Artificial intelligence algorithms have been used on traffic simulations using multiple agents to showcase the CACC vehicles' ability to cooperate and minimize an objective function (Bang and Ahn, 2017; Guériau et al., 2016). Talebpour and Mahmassani proposed that AVs and CAVs should be treated differently in micro simulations. In the same paper they did theoretical work and simulation to test string stability and throughput for different market penetrations of CAVs (Talebpour and Mahmassani, 2016). Finally, section capacity has been calculated according to traffic flow theory for mixed traffic streams and for different lane policies (Chen et al., 2017).

Macroscopic simulation models have also been developed to estimate the impact of automation on a broad perspective and on a strategic level. In 2013 one macroscopic model was proposed to simulate ACC and CACC (Ngoduy, 2013). Another simulation model using modified gas kinetic based traffic to approximate AV and CACC capabilities has been tested for different market penetration of CAVs (Delis et al., 2016). Reservation based intersections using V2I and V2V capabilities to control and increase the intersection flow were compared with signalized intersections using dynamic traffic assignment in (Patel et al., 2016). The network's performance was amplified because of the smaller assumed headways. However, reservation based intersections did not always outperform the signalized intersections. Again using dynamic traffic assignment and static traffic assignment, different pricing strategies for managed lanes were tested showing not significant results for small CACC market penetration rates (Fakharian Qom et al., 2016). It has been shown that another way that CAVs can improve the traffic condition is by routing under a centrally managed, socially aware, routing scheme, which has been tested for five different cities using mobile phone data (Çolak et al., 2016). Results show the ability of a centralized routing scheme to minimize congestion, compared to the individually optimizing routing scenario.

Many of the aforementioned studies try to estimate the impacts of automation to energy consumption and emissions. Additionally, more studies have been done concerning the smoothing of vehicles' velocities (Barth et al., 2013), the potential use of optimized eco controllers (Wang et al., 2012) or strategies to use variable speed limits in order to optimize safety, travel time and sustainability for different CACC penetration rates (Khondaker and Kattan, 2015). Overall it is expected that CAVs will increase efficiency and decrease emissions and energy consumption.

To sum up, the case studies presented in the literature so far mainly focus on macroscopic traffic simulations or microscopic traffic simulations of relatively small networks. In addition, they advocate the *ceteris-paribus* principle, assuming that everything else but the introduction of CAVs stays constant (e.g. the infrastructure, the traffic demand etc.). In this light, the objective of the present paper is to study the effect of different penetration levels for CAVs and of different scenarios of demand evolution inside a complex and realistic case-study and consequently present some first insights regarding the potential positive or negative impact of connectivity and automation in current networks, as well as their interrelationship.

3. Freeway simulation: ring road of Antwerp

This section describes (a) the work carried out to develop the traffic model of the ring road of Antwerp, implemented in Aimsun, (b) the characteristics of the car-following behavior, headway and AV, CAV logic used, (c) the metrics used to assess the simulation results, and finally (d) the scenarios tested with variable penetration rates and traffic demands.

3.1. Antwerp ring road

Antwerp in Belgium has the second largest European port. The city's ring road is used by heavy duty vehicles carrying goods, as well as commuters entering, exiting and crossing the city. Thus, during the rush hour, heavy congestion and saturated traffic flow can be observed. It has been estimated that the ring road is responsible for more than 50% of the total road transport generated pollutant emissions in the city. In the present work, Open Street Maps was used to extract the network's geometry and static information, such as the speed limits and the final network was loaded on Aimsun.. The final supply model of the network consists of 119km of roads with 27 centroids (origin/destination points), 208 sections and 117 intersections and is shown in Figure 1.

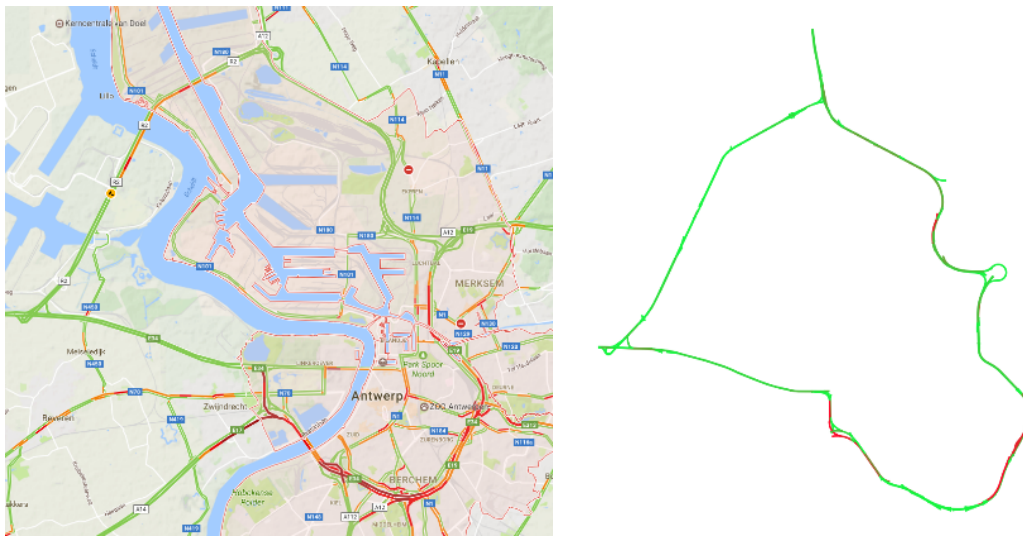


Fig. 1. The network of the ring road of Antwerp. From left to right, (a) a screenshot of the Antwerp region, and (b) the network colored based on the congestion on peak hours.

To simulate realistic traffic conditions, an O/D matrix had to be computed from data of real traffic counts measured during the morning peak hours. The Frank and Wolfe algorithm (Frank and Wolfe, 1956), which is available as a built in tool in the Aimsun software, was used, to adjust an O/D matrix to the observed data.

3.2. Driver models used

Three types of vehicles are used in the present simulation network: Human-driven vehicles, AVs, where the human driver is not responsible to regain control at any point of the trip and CAVs which normally operate as AVs but when needed, they can communicate with other vehicles, forming platoons, exchanging speed and acceleration information, and act according to a different CACC controller logic. Below there is a brief description of the algorithms used for the simulation of the above-mentioned types.

- *Manual Vehicles.* For the simulation of manually driven vehicles, the default option used in AIMSUN is a modified Gipps' car-following model (Gipps, 1981)
- *Autonomous Vehicles (without connectivity).* The simulation of AVs is approximated using the method proposed by Shladover (Shladover et al., 2012). This is a first order model representing ACC vehicle longitudinal behaviour. For the lateral movement, the default AIMSUN behavior was considered. It is worth noting that AVs are forced to obey the speed limits, in contrast to manually driven vehicles that have a speed acceptance factor.
- *Connected and Automated Vehicles.* CAVs in highway simulation scenarios can be expected to have a car following behaviour similar to CACC vehicles while cruising. Hence, the model described by (Talebpour and Mahmassani, 2016) has been used when following a CAV, and the aforementioned AV model if not, assuming that any CAV will behave as an AV when it is not able to exchange information

with its neighbouring vehicles. Also CAVs are forced to obey the speed limits, in contrast to manually driven vehicles that have a speed acceptance factor. Furthermore, lane changing is again modelled based on the default AIMSUN algorithm, using the CAVs particular car following deceleration model.

3.3. Assessment metrics

In the present work, for the assessment of the network's performance per simulation run, the ternary plots between penetration rates of the vehicle types as well as the time series of the harmonic average speed of the vehicles (km/h) are discussed in the results section.

The harmonic average speed of the vehicles (km/h) is calculated using the following equation

$$HS_{sys} = \frac{N_{sys}}{\sum_{i=1}^{N_{sys}} HS_i} \quad (1)$$

Comparing the harmonic average speed over the network with the harmonic average vehicles' desired speed gives an indication of the magnitude of the congestion.

3.4. Market penetration and demand scenarios

As it is already mentioned in the introduction of this paper, the reshape of the transportation as we know it today will probably have a significant impact on the vehicle travel demand. However, it is still quite unclear whether an increase or a decrease in the demand should be expected. Furthermore, the introduction of AV and CAV technology will be performed gradually. In this light, in the present study 21 different combinations of mixed vehicle types were implemented, for penetration rates ranging from 0% to 100% with 20% step. In addition, three different traffic demand scenarios were tested, one with travel demand corresponding to and estimated peak demand based on real counts, another, with estimated peak demand increased by 20% and another decreased by 20%, making the total of 63 scenarios tested. Finally, every scenario involves three hours of simulation, with the second hour being the main interest and the first and last having minimum demand, to load and unload the network smoothly.

4. Results

This section presents the preliminary results of the present work, giving some first insights on the anticipated impact of connectivity and/or automation in future transport systems. To explore the impact of the introduction of AVs and CAVs to the freeway network 63 scenarios were tested. Data about the situation on the network were gathered for every 10 minutes interval. For the first 20 minutes the data are not collected as it is considered as a warm up phase, in order to load the network with vehicles. The demand changes to the peak hour demand after the first hour of simulation, and then changes again to the unloading phase demand after the end of the second hour of simulation. Because of the length of the network, the effects of the peak hour demand are observable more clearly between the 80th minute (20 minutes after the completion of the first loading hour) and the 140th minute (20 minutes after the beginning of the third unloading hour), since the traveling time inside the network of many vehicles can be more than fifteen minutes, even in uncongested conditions. Data representing low demand refer to the interval from the 20th minute to the 80th and peak hour is represented by the data from the 80th minute to the 140th.

The harmonic average speed of the network over different time moments is considered as the most indicative metric for the status of the network in our results. It is calculated in km/h as the average space mean speed of all the vehicles. The harmonic average speed is considered to be related with the average delay in the network. By the average speed it can be deduced if the network is close to capacity or not, and the delay time is one of the factors that the network users would like to minimize.

In Fig. 2 the harmonic average speed is presented corresponding to the second-peak-hour demand, for all three possible demands in ternary plots (estimated, increased and decreased demand). Each corner represents the case of 100% ratio of the vehicle type that the corner is labelled with. The space in the triangles is representing the different penetration rates of CAVs and AVs in the mixture of vehicles. On every point inside the triangle the ratio of each type is in inverse proportion to the distance to the corner. The three ternary plots presented in the figure

illustrate the three different traffic demands, while the colours indicate the harmonic average speeds over the network.

Based on the results it is obvious that AVs introduction over the network has negative impact even at very low penetration rates. This can be linked with increase headways in comparison with human-driven vehicles, which are imposed mainly for safety-related reasons. Human drivers take risks while driving, trying to predict the movement of other neighbour vehicles. On the other hand, AVs should not take any risk under any condition, which eventually leads in more conservative headway thresholds on the road.

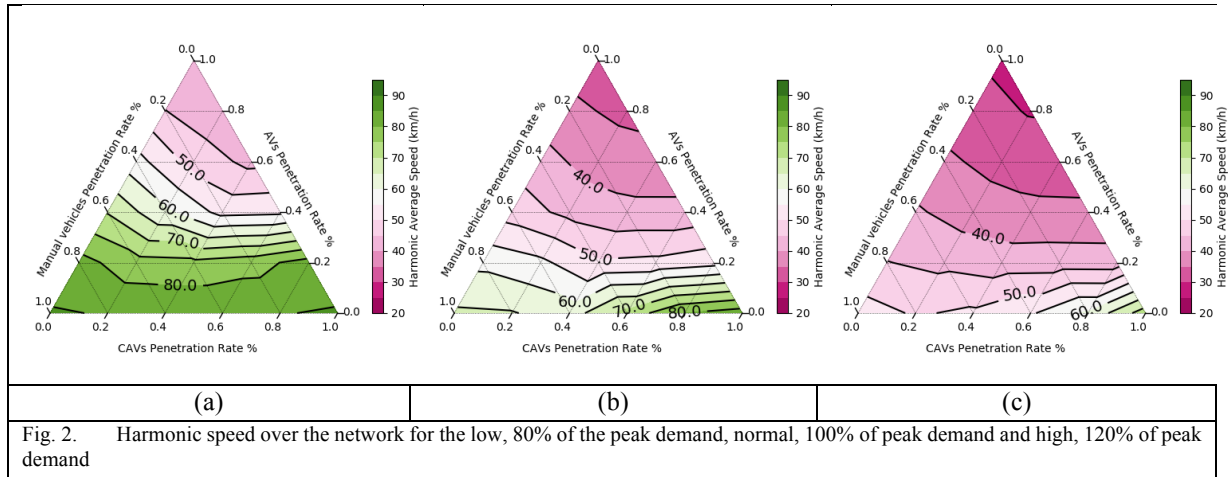


Fig. 2. Harmonic speed over the network for the low, 80% of the peak demand, normal, 100% of peak demand and high, 120% of peak demand

The negative impact of AVs is more obvious in bottlenecks, when they have to merge or change lanes. The gap needed by an AV to perform a lane changing manoeuvre is much larger than gaps accepted by human drivers since AVs cannot take risks, and their maximum deceleration is less than that of a manually driven vehicle, for safety and comfort reasons. Moreover, the maximum acceleration in AVs is lower than the one on manual vehicles and this is something that it can be already observed in ACC systems of commercially available vehicles. 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.

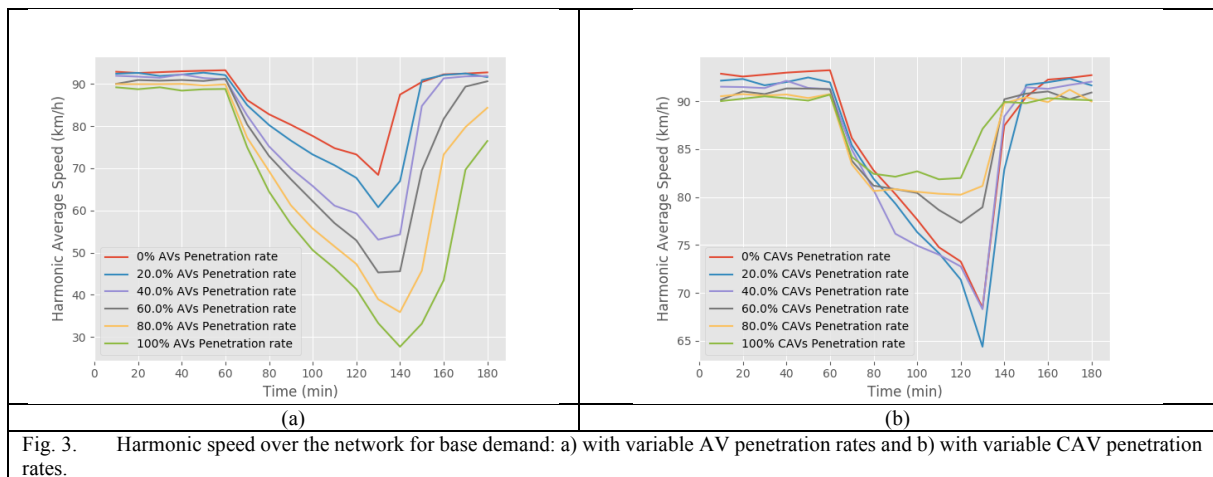


Fig. 3. Harmonic speed over the network for base demand: a) with variable AV penetration rates and b) with variable CAV penetration rates.

In contrast to AVs, the impact of CAVs in the network is positive and it is improved as the penetration of CAVs increases. 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. Moreover, on low penetration rates, the probability of a CAV following another CAV to form a connected platoon is much smaller than the probability of a CAV following a manually driven vehicle or an AV. Hence most CAVs act as AVs, demanding larger headways to cruising or lane changing. The probability of two CAVs to be able to connect increases with the introduction of more CAVs over the network. With higher penetration of CAVs gaps are smaller, lane changes

are easier and the traffic streams are more stable, able to absorb oscillations without traffic breakdown occurring. Consequently, the harmonic average speed remains high, even for the large demand scenarios.

In Figure 3 the time series of the harmonic average speed is presented for the network on various penetration rates of AVs and CAVs respectively. The graphs can be divided in three phases; the first hour when the network is loading and the demand is still in very low levels; the second hour which corresponds to peak demand and the network becomes heavily congested and the third hour when the network is unloading and the demand returns to very low levels. For AVs, it is clear that as the penetration of the vehicles in the network increases the harmonic average speed reduces a lot. As approaching to the end of the second hour the network is congested and on the 100% AV scenario the speed drops down to 30km/h. During the third hour and the unloading phase, the more congested the network is the slower it recovers. It is worth noting that for over 60% penetration rates the harmonic average speed did not reach the normal values of about 90km/h after the end of the third hour.

On high penetration rates, the harmonic average speed of the network remains at high values over 80km/h which clearly shows that CAVs can increase the capacity of the network. As there are less vehicles with no communication capabilities on the network, CAVs travel in platoons and therefore, they can dampen oscillations and assist the flow at bottlenecks. In low penetration rates the CAVs are not utilizing fully their connectivity as there are not many other CAVs on the network to communicate with. As a result, they operate like AVs, damaging the networks conditions as it is already mentioned above. Communication with infrastructure or use of optimal control algorithm to cooperate may restore the benefits even on low penetration rates and enhance them on higher. However, reviewing control algorithms and testing them is outside the scope of the present paper.

Finally, it is worth mentioning that for both AVs and CAVs for the first hour the harmonic average speed is lower than the based scenarios (100% manually-driven vehicles). This can be justified by the fact that human-driven vehicles tend to take more risks which in microsimulation can be interpreted as higher maximum acceleration values, less respect to the road limits, aggressiveness on on/off ramps etc.

5. Conclusions

The present paper demonstrates some preliminary results regarding the anticipated introduction of automated and connected automated vehicles on a real world network. As case study, the ring road of Antwerp, a city in Belgium with the second largest European port thus generating heavy traffic conditions on the adjacent road network, has been selected. The base demand was calculated from real traffic counts and the network was modelled to closely represent the existing infrastructure. For the simulation of AVs and CAVs behavior, state of the art car following models that describe the behavior of ACC and CACC capable vehicles were used. The Aimsun traffic simulation platform has been used to code the different vehicle logics and to simulate the impact on traffic.

A number of different scenarios were tested to account for the impact of various different mixtures of manually driven vehicles, AVs and CAVs. Moreover, the tests were carried out for three different traffic demands, 80% 100% and 120% of the base scenario (estimated peak demand) and 6 variable penetration rates from 0% to 100%. All the possible combinations between the variable penetration rates per vehicle type and the three different traffic demands led in total to 63 simulations of 3-hour duration each.

The results concerning AVs showed that they deteriorate the situation over the network. On low traffic demands, manually driven vehicles outperformed AVs due to their nature to take more risks and overcome the speed limits. Average speed on the network has been decreasing while density and congestion have been sharply increasing for high penetration rates of AVs. The desired time gap of the AVs proved to have substantial influence on the results, in some cases more than the traffic demand. Those negative effects are attributed to the AVs inability to predict the neighboring vehicles' movement during lane changing manoeuvres, and take risks.

CAVs on the other hand proved to be beneficial to the network under some conditions. Very low penetration rates of CAVs have a small negative result, as they act mostly as AVs since there are not many vehicles to exchange information with. Also on low traffic demands, manually driven vehicles outperformed CAVs even on higher penetration rates due to the CAVs inability to overcome the speed limits. However, on higher demands and high penetration rates, CAVs are able to accept smaller gaps while cruising or maneuvering on the network, to prevent the formation of traffic oscillations and to improve the network level of performance, withstand larger densities with high average speed and prevent bottleneck from disrupting the traffic flow.

These preliminary results seem to confirm the effectiveness of the strategy put forward by the European Commission to consider vehicle connectivity as the first necessary step in the transition towards the automation of the entire transportation sector. The same choice is not shared by all Governments and although the role of

connectivity is acknowledged also elsewhere, the work carried out by the European Commission can represent a considerable competitive advantage in the future race towards a safer and more efficient road transport.

Future research by the authors will focus on expanding the present work by introducing more simulation scenarios, assessing the sensitivity of the algorithms' parameters and trying to define in more detail the interactions between human-driven vehicles, AVs and CAVs on highway scenarios. Finally, the authors want to study the opportunities introduced by a system/segment/network coordinator to better manage vehicle movements so to achieve a system optimum in terms of multiple variables such as travel time, energy consumption and emissions. The relevant political implications of introducing such a coordination systems will also be considered and assessed.

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