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Traffic & environmental impact assessment under distinct operational speeds for automated shuttle bus services

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Abstract

Connected and automated transport systems are expected to be the first to align with their large-scale business cases by enhancing urban transportation activities. The present study aims to assess the traffic and environmental impacts of different operational speeds of automated shuttle bus service through traffic microscopic simulation. In this context, different scenarios were formulated simulating the Villaverde district in Madrid, Spain. The analysis of the results provided multiple measurements quantifying the impacts of automated services in different Market Penetration Rates (MPRs) of Connected and Autonomous Vehicles (CAVs) on network and service level. The results revealed that a higher operational speed of an automated shuttle service operates more efficiently for lower CAV MPRs, while operational speed seems to not impact traffic and environmental conditions in higher MPRs.

Keywords: Connected And Autonomous Vehicles; City Automated Transport Systems; Automated Public Transport; Traffic Microsimulation; Simulation

1. Introduction

The automobile industry has evolved continuously and intensively over the last decades and hence a significant advance in technologies that are integrated with state-of-the-art vehicles can be observed (Rajasekhar and Jaswal, 2016). The latest advances in technology bring computerization into the vehicles (Fagnant and Kockelman, 2015) and this computerization enabled the automobile industry to plan and develop autonomous vehicles; the next generation of upcoming vehicles (Rajasekhar and Jaswal, 2016). Automation enables vehicles to drive and navigate on their own

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without direct human input (Rajasekhar and Jaswal, 2016). The highest level of autonomy can be considered the SAE level 5, a fully automated vehicle without any human input (SAE, 2016) and simultaneously this vehicle will be connected with the rest of the traffic participants. This type of vehicle is defined as Connected and Autonomous Vehicle (CAV) and it is predicted to have a dominant market share in 2050 assuming CAV prices fall at a 15% to 20% yearly rate. (Talebian and Mishra, 2018).

CAVs have the potential to change the transportation systems fundamentally Fagnant & Kockelman (2015). Specifically, CAVs are expected to increase aspects such as road capacity, fuel efficiency, and lower environmental emissions (Elvik, 2021; Fagnant and Kockelman, 2015; Mersky and Samaras, 2016; Ye and Yamamoto, 2018), however, this outcome is highly dependent on the parametrization of autonomous vehicles and automation systems. Furthermore, road safety level will be enhanced with the CAV evolution since road collisions will be prevented. According to recent studies, depending on the Market Penetration Rates (MPR) of CAVs, traffic conflicts could be reduced dramatically (Papadoulis et al., 2019; Mourtakos et al., 2021).

In terms of passenger benefits, a large section of the population, including the elderly, children, and disabled, will be able to commute, in contrast to current conditions with conventional vehicles. Furthermore, the use of shared automobiles will increase since commuters will no longer own their cars and instead rely on on-demand services. Regarding the advantages at a passenger level, a great proportion of the population, such as the elderly, children, and disabled will have the opportunity to commute in contrast with the prevailing conditions regarding conventional vehicles. Furthermore, shared vehicles will increase radically as commuters will not own their vehicle, but will use an on-demand service.

Automated shuttle bus services or Connected Automated Transport Systems (CATS) are expected to be the first to align with their large-scale business cases by enhancing urban transportation activities and making transit systems more attractive to passengers. The gradual increase in the MPR of automated transit services appears to have the capabilities of reducing travel time and CO_2 emissions (Ziakopoulos et al., 2021). More specifically, point-to-point automated shuttle bus services that use a dedicated lane, present decreased delay time and CO_2 emissions compared to mixed traffic conditions (Oikonomou et al., 2020). Another recent study revealed that participants who used a real-conditions test-ride of autonomous shuttle services, responded that the one attribute that are most concerned is the speed of shuttle service (Chen, 2019). In this direction, the current study identifies and examines the traffic and environmental impacts of automated shuttle bus services at various speeds. The current study was motivated by the discovery that there is a gap in the existing literature regarding the investigation of different operational speeds of a fixed automated shuttle service. This study was inspired by research conducted within the EU H2020 SHOW project, which aims at shared automation operating models development for worldwide adoption.

The current study identifies and examines the traffic and environmental impacts of automated shuttle bus services at various speeds for various MPRs through simulation approaches in order to investigate more profoundly apart from the AV shuttle service-related impacts, the network-level impacts as well. Simulations were chosen for the purpose that the examined hypothetical scenarios would not be feasible to be conducted in another way with the same level of detail as well as simulation methods have been used to investigate the effects of AVs and their performance (Talebpour et al., 2017). The inputs to the simulation originate from a range of sources, including network geometry, traffic volume, and modal split. More specifically, the data generated by the microscopic simulation can be used to make a preliminary, descriptive assessment of a number of impacts. Every car is monitored as it interacts with other vehicles and the surroundings. Furthermore, microscopic simulation is commonly used to evaluate new traffic control and management technologies as well as to analyze current traffic operations (Owen et al., 2000). Modeling traffic flows allows researchers to simulate the driving of every vehicle inside the considered transportation network and give several traffic-related impacts while taking traffic features into consideration, resulting in more accurate emissions estimations (Lopez et al., 2018; Zhu and Zhang, 2017).

The present research is inspired and conducted within the EU HORIZON 2020 "SHOW" project that aims to support the migration path towards effective and persuasive sustainable urban transport through technical solutions, business models, and priority scenarios for impact assessment, by deploying shared, connected, electrified fleets of automated vehicles in coordinated Public Transport (PT), Demand Responsive Transport (DRT), Mobility as a Service (MaaS) and Logistics as a Service (LaaS) operational chains in real-life urban demonstrations.

This study is structured as follows; initially, the current section presents a brief introduction to the study aim. Then, the methodology follows, including two main subsections. The first one relates to the simulation aim, preparation, and simulation network. The second one relates to the measurements that can be derived and analyzed by this study. After that, results are presented by including plots with the examined measurements derived from the simulation along with outcomes related to the MPR in combination with distinct operational speeds of the shuttle service. Finally, overall conclusions are presented, which include a brief summary of the purposes of the study and its findings, as well as how stakeholders or policymakers might benefit from it, as well as study limits and future research proposals.

2. Methodology

2.1. Simulation Network and Shuttle Service

In order to investigate an automated shuttle bus service and further examine its operational speed, the microscopic simulation method was selected. Microscopic simulation has the ability to extract more detailed insights since it provides information related to individual vehicles by modelling traffic flows at a high level of detail. In this context, different scenarios were formulated using the Aimsun Next mobility software simulating the Villaverde district network in Madrid, Spain.

Focusing on the network specifications, the study network consisted of 365 nodes and 668 road segments, as depicted in Fig. 1. The Origin-Destination (OD) matrices consisted of 30 centroids, and the travel demand contained 5,784 car trips and 716 truck trips within the morning peak hour. In addition, the total length of road sections is 23 km and the network size reaches approximately 2 km^2. Furthermore, the examined Villaverde transport network includes, in current conditions, 23 conventional bus lines (not necessarily with origin and destination inside the examined area) and 39 public transport stops, which were also included in the simulation model as well as frequencies and waiting times at stops, obtained from bus operator websites.

An automated shuttle bus service was implemented in the study network, operating in parallel with the existing public transport. Its line connected the “La Nave”, a public facility that encompasses numerous activities, with the “Villaverde Bajo Cruce” subway station, shown in Fig. 1. The service included one shuttle bus with a frequency of 15 minutes, and consequently there were four departures per hour. The service circular route had a total length of 1.6 km and had two bus stops in total. The electric bus had a total capacity of 60 passengers plus 25 passenger seating. Its dimensions were 12 m in length and 2.55 m in width. The maximum desired speed of the bus was 60 km/h, maximum acceleration 1.36 m/s^2, maximum deceleration 10 m/s^2 and weight 15,845 kg.

Fig. 1. Villaverde network in Aimsun Software and the shuttle service: (a) two connecting points; (b) circular route.

Finally, the geometry of the study area was exported from the OpenStreetMap digital map platform. The accuracy of the road geometry was cross-validated with random sample comparison with further maps. The data for each road segment that were taken into account were the road geometric as well as functional characteristics namely length, width, number of lanes, directions, free flow speed and capacity. Also, the characteristics of nodes that were included in the model network were the following: allowed movements, number of lanes per movement, priority, traffic light control plans, free speed flow and capacity. In addition, the microscopic model included volume data that were collected for the year 2018 from about 80 detectors. The necessary traffic data, as well as Automated Driving (AD) shuttle bus features, were provided by EMT Madrid (Empresa Municipal de Transportes de Madrid - www.emtmadrid.es) which is responsible for planning public urban transport in the city of Madrid, Spain. The detectors recorded traffic volume in vehicles per time. Those data were used in order for the aforementioned OD matrices to be created.

2.2. Simulation Scenario

Three sets of simulation scenarios were investigated: i) different CAV market penetration rates within prevailing traffic demand (0%-100% increasing by 10%) applied to passenger cars and trucks, ii) with or without operation of the automated shuttle bus service and iii) distinct operational speeds for the automated shuttle bus service. Overall, the following scenarios related to shuttle service operation were formulated:

- Baseline (no automated shuttle bus service operation)
- Operation of automated shuttle bus service with 15 km/h operational speed
- Operation of automated shuttle bus service with 30 km/h operational speed
- Operation of automated shuttle bus service with 45 km/h operational speed

For each of the above scenarios, different CAV market penetration rate scenarios, from 0% to 100% in 10% increments, were also simulated. Specifically, the introduction of CAVs replaced the respective conventional vehicles percentage. Throughout all the shuttle service scenarios and MPRs, traffic demand and characteristics, as described previously in Section 2.1, kept constant for comparison purposes in the analysis. Future traffic demand was not considered and predicted, as the main scope of the current study is to investigate distinct operational speeds for bus services. Hence, by changing traffic demand, it would be infeasible to compare directly the impact of operational speed on traffic and the environment, therefore, this is left for future research. Therefore, 44 scenarios were simulated in total (11 MPR scenarios for each of the 4 shuttle service operation scenarios). Background information related to the modelling of the simulated parametrization of CAVs can be found at the following link (https://levitate-project.eu/downloads/) since is based on forthcoming publications and deliverables of the LEVITATE project. Additionally, with regards to each scenario, 10 different replications with random seeds were simulated as well. The simulation duration of each scenario was one hour, and the simulation time step was 10 minutes. The simulated CAVs, as well as automated shuttle bus service, were assumed to be exclusively electric. Moreover, the change in CAV MPRs applied to passenger cars and trucks but not to public transport buses which remained conventional for all the examined scenarios.

2.3. Examined Measurements

Within the SHOW project, Key Performance Indicators (KPIs) for the evaluation of impacts of systems and services within the area of CAV were defined (Anund et al., 2020). In addition, the KPIs were matched to research questions or the main target to ensure that all CAV systems and service activities are adequately covered by a holistic collection of related to simulation KPIs. The sources identified within the impact assessment of the SHOW project also led to the definition of relevant KPIs divided into categories such as Traffic safety, Traffic efficiency, and Environment and energy efficiency. Based on the project-defined KPIs and those that can be exported through the microscopic simulation, multiple measurements quantifying the impacts of CAVs in different traffic conditions were extracted. These impacts were influenced by the CAV MPR as well as the automated shuttle service operation and are the following:

Traffic efficiency
- Delay Time: mean delay time (sec/km)
- Speed: mean speed (km/h)
- Total Distance Travelled: total distance travelled of the vehicles that exited the network (km)
- Travel Time: mean travel time (sec/km)

Environment and energy efficiency
- CO_2 Emissions: total carbon dioxide emissions (g)
- NO_x Emissions: total nitrogen oxides emissions (g)
- PM Emissions: total particulate matter emissions (g)

The above measurements took into account the performance of the entire traffic within the network. In addition, some measurements (i.e., automated shuttle service delay time, speed and travel time) are revealed focusing on the performance exclusively of the investigated automated shuttle bus service.

The environmental impacts obtained by the simulation using the Aimsun software and were calculated by applying the formula developed by Panis et al. (2006). This model computes carbon dioxide (CO_2), nitrogen oxides (NO_X) and particulate matter (PM).

3. Results & Discussion

In Fig. 2 and Fig. 3, the traffic and environmental measurements on the network level, extracted from microscopic simulation, namely delay time, speed, total distance travelled, and CO_2, NO_x, PM traffic emissions, are presented.

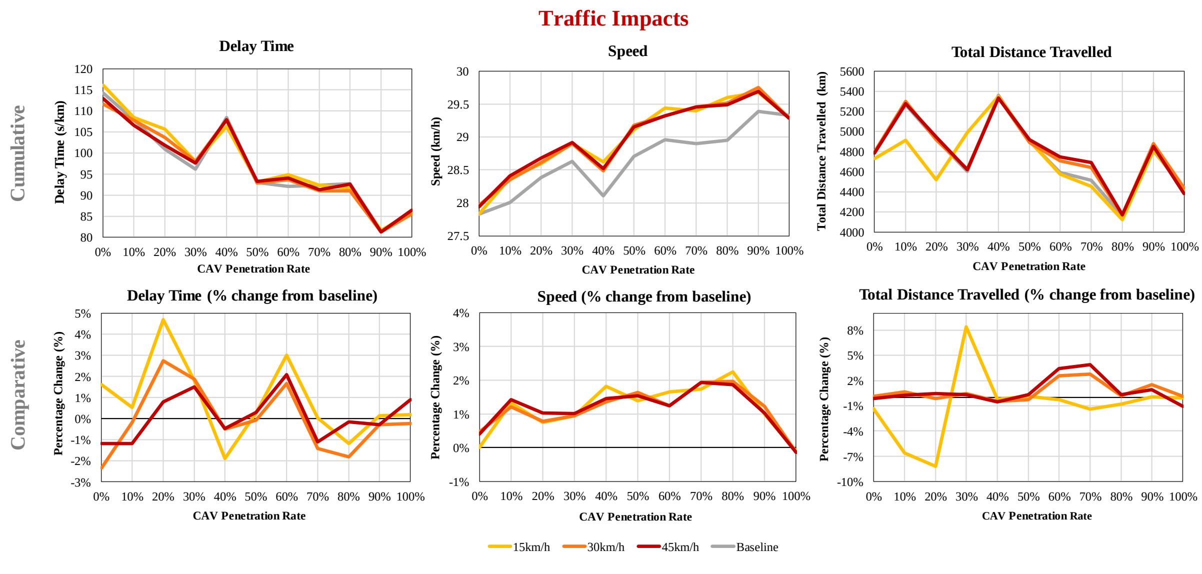

Fig. 2. Network level traffic impacts.

Investigating the general trend, it can be concluded that on the network level by increasing the CAV MPR the traffic conditions were improved, as shown in Fig. 2. This improvement can be substantiated by figuring out the core enhancements of the modeled CAV within the simulation prototypes; having advanced sensing and cognitive ability, data fusion usage, confident in taking decisions, small gaps, early anticipation of lane changes than human-driven vehicles, and less time in give way situations. More specifically, the speed was increased, while delay time, and distance travelled were decreased. Regarding the shuttle bus service operation, overall there were no major differences between the different operational speeds on network level and hence additional comparative plots were created in the second row of Fig. 2 in order to compare the different speed services to the baseline (without an Automated Driving

(AD) shuttle service existence). It can be concluded that the higher operational speed services (30 and 45 km/h) led to lower delay time and did not seem to affect driven kilometers for CAV MPRs under 30% compared to the automated shuttle bus service with 15 km/h, when comparing to the baseline scenario. Furthermore, the same trend in delays was noticed for higher CAV MPRs (above 30%) between the examined services. Similarly, the same trend was also shown in mean speed for all CAV MPRs, while a slight increase was presented compared to the baseline scenario. Moreover, the total distance travelled remained unaffected for the majority of the MPR scenarios. Overall, it was revealed that the lowest operational speed service presented higher fluctuations across the initial MPRs compared to the other two services, while the impacts of the three services were then stabilized in higher MPRs.

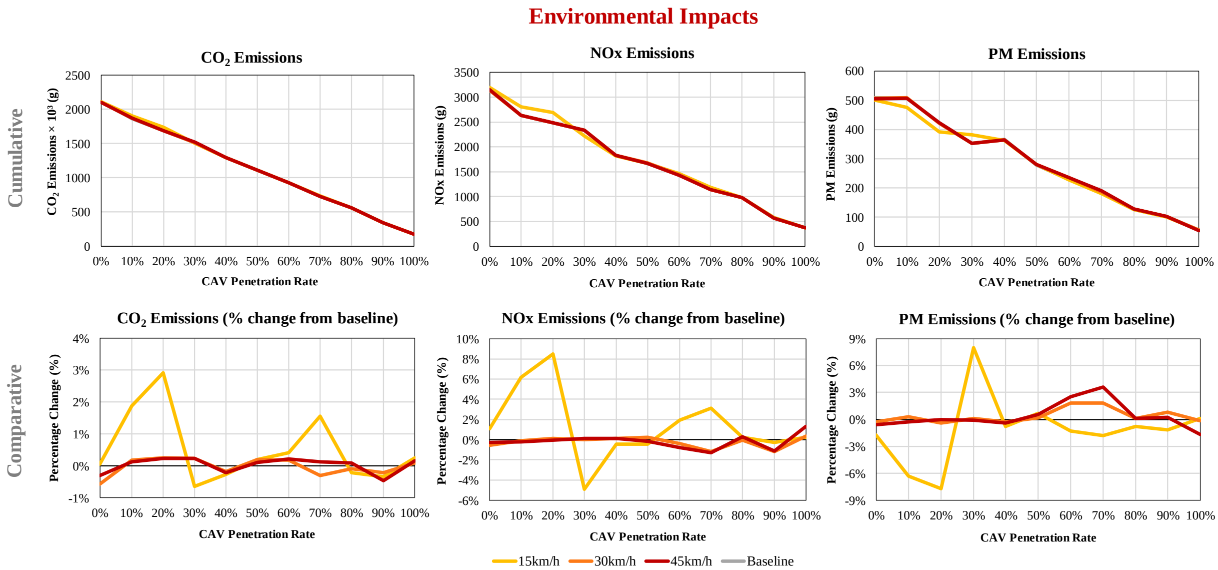

Fig. 3. Network level environmental impacts.

Analyzing the general trend, it can be concluded that on the network level by increasing the CAV MPR the environmental conditions were improved fundamentally due to the electrification of the CAV fleet considered (Fig. 3). More specifically, CO_2, NOx and PM emissions were decreased linearly and drastically for increasing the MPR. Taking into account the second row of Fig. 3, which includes comparative plots, as a general outcome can be concluded that, 30 and 45 km/h operational speed services were quite consistent and close to the baseline across the MPR scenarios, while the 15 km/h speed service fluctuated drastically below 70% MPR. Specifically, the lowest operational speed service led to higher CO_2 and NO_x traffic emissions and lower PM emissions in lower MPRs (below 30%). The increase in CO_2 and NO_x is correlated to the respective increase in delays as shown in Fig. 2, and hence, the more congested conditions led to higher levels of traffic emissions. On the other hand, the PM levels for the respective CAV MPRs were decreased, as fewer kilometers were driven due to the congested conditions (Fig. 2) and the fact that PM emissions were produced from tire wear, brake-wear and vehicle-induced resuspension of road dust (WHO, 2013). For higher MPRs, the environmental impacts were normalized and no significant differences between the studied services were noticed.

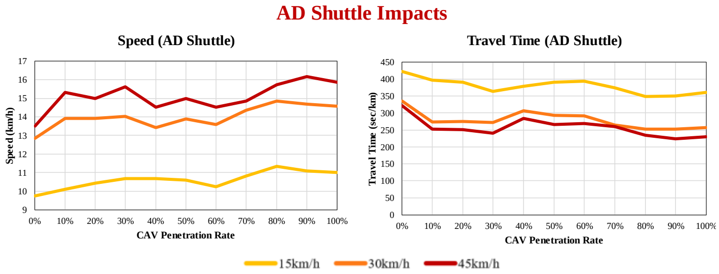

Fig. 4. Automated shuttle bus service level results.

Focusing on the automated shuttle bus service level results, as shown in Fig. 4, it can be concluded that by increasing the CAV MPR, shuttle service mean speed was slightly increased, while travel time was decreased. It can also be extracted by analyzing Fig. 4 that services with 30 and 45 km/h fluctuated similarly through the increasing CAV MPR. As it is logical, 45 km/h throughout all the MPR scenarios recorded a higher speed and lower travel time compared to the other-speed services. The service with the 15 km/h operation records disproportional lower speed and travel time compared to the two other-speed services across the MPR scenarios.

4. Conclusions

To conclude, the present study aims to assess the impacts of different operational speeds of automated shuttle bus services through the traffic microscopic simulation method. For this purpose, a microscopic simulation analysis was conducted to provide multiple measurements quantifying the impacts of CAVs in different traffic conditions. Different scenarios were formulated using the Aimsun Next mobility modelling software in the Villaverde district of Madrid, Spain. More specifically, three simulation sets were investigated: i) different CAV market penetration rates within prevailing traffic demand (0%-100% increasing by 10%) applied to passenger cars and trucks, ii) with or without operation of the automated shuttle bus service and iii) distinct operational speeds for the automated shuttle bus service, namely 15 km/h, 30 km/h and 45 km/h.

More specifically, microscopic simulation results revealed that traffic as well as environmental conditions were improved when more CAVs exist within the network. The environmental improvements can be substantiated due to electrification and the traffic improvements due to advanced sensing and cognitive ability, data fusion usage, confident in taking decisions, small gaps, early anticipation of lane changes than human-driven vehicles, and less time in give way situations. The network average speed was increased, while delay time, distance travelled and traffic emissions were decreased. Focusing on the shuttle bus service operation, no major differences between the different operational speed services were noticed on network level. However, it can be noticed that the higher operational speed services (30 and 45 km/h) presented lower delay time as well as approximately the same driven kilometers for CAV MPRs under 30% compared to the lowest operational speed shuttle service (15 km/h). Furthermore, the same trend in delays was noticed for CAV MPRs above 30%. Overall, it was revealed that the lowest operational speed service presented higher fluctuations across the initial MPRs compared to the other two services, while the impacts of the three services were then stabilized in higher MPRs. Therefore, results indicated that a higher operational speed for an automated shuttle bus service operates more efficiently for lower MPRs of CAVs, while operational speed seemed to not impact traffic and environmental conditions in higher CAV MPRs. Finally, CO_2, NO_x and PM levels were significantly reduced increasing the MPR and the shuttle services of 45 km/h and 30 km/h operational speeds were consistent with the baseline (without a service) compared to the 15km/h service, which fluctuated more for lower MPRs. For higher MPRs, the environmental impacts were normalized and no significant differences between the three services were noticed.

Focusing on the results referring to automated shuttle bus service level, it can be concluded that by increasing the CAV MPR, shuttle service mean speed was increased, while travel was decreased. Furthermore, the three different services revealed significantly different results for all MPRs. As was expected, the service with the 15 km/h operational speed presents the lowest mean speed, and the highest travel time compared to the other two services. Similarly, the service of the 45 km/h operational speed presented the highest mean speed, and the lowest travel time.

Finally, the main contribution of the present study is that the obtained impacts could guide stakeholders in optimizing the traffic assessment procedures through the microsimulation method by emphasizing critical aspects. Moreover, from the knowledge gained from the microsimulation, insights will be provided for critical factors that should be taken into account for the development of sustainable urban mobility. For future research aspects, additional impacts in relation to other services need to be further investigated, along with taking into account different networks, vehicle types as well as automation levels. Taking into account research findings, additional experiments testing services with additional operational speeds (apart from the examined ones) as well as investigating different parameters of the autonomous shuttle buses (e.g. headway, acceleration and deceleration, etc.) could enrich the impact assessment of automated transport systems. The present study does have certain limitations. Since traffic microsimulation was employed, assumptions regarding CAVs modelling were unavoidable. As a consequence, additional KPIs, except for the examined ones, will be able to shed light on further impacts of automated shuttle service operation on traffic and the environment as well as on road safety that were not investigated in the present research.

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References

Anund, A., Dahlman, A.S., Rombaut, E., Robinson, D., Vanhaverbeke, L., Jany-Luig, J., Schauer, N., Hülsermann, J., Heinen, M., 2020. D9.2: Pilot experimental plans, KPIs definition & impact assessment framework for pre-demo evaluation.

Chen, C., 2019. Factors affecting the decision to use autonomous shuttle services : Evidence from a scooter-dominant urban context. Transp. Res. Part F Psychol. Behav. 67, 195–204.

Elvik, R., 2021. Can the impacts of connected and automated vehicles be predicted? Danish J. Transp. 3, 1–13.

Fagnant, D.J., Kockelman, K., 2015. Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. Transp. Res. Part A Policy Pract. 77, 167–181.

Lopez, P.A., Behrisch, M., Bieker-Walz, L., Erdmann, J., Flotterod, Y.P., Hilbrich, R., Lucken, L., Rummel, J., Wagner, P., Wiebner, E., 2018. Microscopic Traffic Simulation using SUMO. IEEE Conf. Intell. Transp. Syst. Proceedings, ITSC 2018-Novem, 2575–2582.

Mersky, A.C., Samaras, C., 2016. Fuel economy testing of autonomous vehicles. Transp. Res. Part C Emerg. Technol. 65, 31–48.

Mourtakos, V., Oikonomou, M.G., Kopelias, P., Vlahogianni E.I., Yannis G., 2021. Impacts of autonomous on-demand mobility service: A simulation experiment in the City of Athens. Transportation Letters. DOI: 10.1080/19427867.2021.2000571.

Oikonomou, M.G., Orfanou, F.P., Vlahogianni, E.I., Yannis, G., 2020. Impacts of Autonomous Shuttle Services on Traffic, Safety and Environment for Future Mobility Scenarios. 2020 IEEE 23rd International Conference on Intelligent Transportation Systems (ITSC). Rhodes, Greece, 1–6. DOI: 10.1109/ITSC45102.2020.9294576.

Owen, L.E., Zhang, Y., Rao, L., McHale, G., 2000. Traffic flow simulation using CORSIM. Winter Simul. Conf. Proc. 2, 1143–1147.

Panis, L.I., Broekx, S., Liu, R., 2006. Modelling instantaneous traffic emission and the influence of traffic speed limits. Sci. Total Environ. 371, 270–285.

Papadoulis, A., Quddus, M., Imprialou, M., 2019. Evaluating the safety impact of connected and autonomous vehicles on motorways. Accid. Anal. Prev. 124, 12–22.

Rajasekhar, M. V., Jaswal, A.K., 2016. Autonomous vehicles: The future of automobiles. 2015 IEEE Int. Transp. Electrif. Conf. ITEC-India 2015 1–6.

SAE, 2016. Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles 42–56.

Talebian, A., Mishra, S., 2018. Predicting the adoption of connected autonomous vehicles: A new approach based on the theory of diffusion of innovations. Transp. Res. Part C Emerg. Technol. 95, 363–380.

Talebpour, A., Mahmassani, H.S., Elfar, A., 2017. Investigating the effects of reserved lanes for autonomous vehicles on congestion and travel time reliability. Transp. Res. Rec. 2622, 1–12.

WHO Technical report, 2013. Review of Evidence on Health Aspects of Air Pollution. REVIHAAP Project. www.euro.who.int/__data/assets/pdf_file/0004/193108/REVIHAAP-Final-technical-report-final-version.pdf.

Ye, L., Yamamoto, T., 2018. Modeling connected and autonomous vehicles in heterogeneous traffic flow. Phys. A Stat. Mech. its Appl. 490, 269–277.

Zhu, W.X., Zhang, J.Y., 2017. An original traffic additional emission model and numerical simulation on a signalized road. Phys. A Stat. Mech. its Appl. 467, 107–119.

Ziakopoulos A., Oikonomou M.G., Vlahogianni E.I., Yannis G., 2021. Quantifying the implementation impacts of a point to point Automated Urban Shuttle Service in a large scale network. Transport Policy, Volume 114, Pages 233-244. DOI: 10.1016/j.tranpol.2021.10.006.