Impacts of autonomous transit services on urban networks: The case of Athens, Greece

**Maria G. Oikonomou[1], Vasileios Mourtakos[1], Julia Roussou[1],
Apostolos Ziakopoulos[1], Eleni I. Vlahogianni[1], George Yannis[1]**

[1]National Technical University of Athens, Department of Transportation Planning and Engineering,
5 Heroon Polytechniou str., GR-15773, Athens, Greece
E-mail: moikonomou@mail.ntua.gr

Abstract

Connected and automated vehicles (CAVs) are expected to lead to increased capacity and reduced accidents and pollution. Regarding the connected automated transport systems (CATS), shuttle bus services are expected to be the first to align with their large-scale business cases increasing urban transport activities. This study aims to examine the impacts of autonomous transit services on traffic, environment and safety in an urban environment, through several use cases and scenarios executed on a microsimulation testbed network. Three different autonomous public transit services were implemented and the simulation scenarios differed in terms of CAV market penetration rate, traffic conditions and service operation. Point-to-point shuttle bus service operation in a small-scale network led to increased delays and driven kilometers, while operations in a large-scale network did not show significant differences. On-demand shuttle service showed decreased delays and kept constant the driven kilometers. The existence of dedicated lanes did not affect traffic.

Keywords: *traffic microsimulation, connected and autonomous vehicles, city automated transport systems, autonomous transit services, impact assessment*

Περίληψη

Τα συνδεδεμένα και αυτόνομα οχήματα (CAVs) αναμένεται να οδηγήσουν σε αύξηση της ικανότητας του δικτύου και σε μείωση των ατυχημάτων και της ρύπανσης. Όσον αφορά τα συνδεδεμένα αυτοματοποιημένα συστήματα μεταφορών (CATS), οι υπηρεσίες μεταφοράς με αυτόνομα λεωφορεία αναμένεται να είναι οι πρώτες που θα εναρμονιστούν με τα μεγάλης κλίμακας επιχειρηματικά τους σχέδια, αυξάνοντας τις δραστηριότητες των αστικών μεταφορών. Ο στόχος της παρούσας μελέτης είναι να εξεταστούν οι επιπτώσεις των αυτόνομων υπηρεσιών συγκοινωνίας στην κυκλοφορία, στο περιβάλλον και στην οδική ασφάλεια σε αστικό περιβάλλον, μέσω της προσομοίωσης διάφορων υπηρεσιών και σεναρίων σε ένα δοκιμαστικό δίκτυο. Προσομοιώθηκαν τρεις διαφορετικές αυτόνομες υπηρεσίες δημόσιας συγκοινωνίας και τα σενάρια διέφεραν ως προς το ποσοστό διείσδυσης των CAVs στην αγορά, την κυκλοφορία και τις λειτουργίες των υπηρεσιών. Η εφαρμογή της υπηρεσίας εξυπηρέτησης από σημείο σε σημείο σε δίκτυο μικρής κλίμακας οδήγησε σε αυξημένες καθυστερήσεις και οδηγούμενα χιλιόμετρα, ενώ σε δίκτυο μεγάλης κλίμακας δεν παρουσίασαν σημαντικές διαφορές. Η υπηρεσία μεταφοράς κατ' απαίτηση παρουσίασε μειωμένες καθυστερήσεις και σταθερά οδηγούμενα χιλιόμετρα. Η χρήση ειδικών λωρίδων από τα αυτόνομα λεωφορεία δεν επηρέασε την κυκλοφορία.

Λέξεις-κλειδιά: *μικροσκοπική προσομοίωση κυκλοφορίας, συνδεδεμένα και αυτόνομα οχήματα, συνδεδεμένα και αυτοματοποιημένα συστήματα μεταφορών, αυτόνομες υπηρεσίες συγκοινωνίας, αξιολόγηση επιπτώσεων*

1. Introduction

Connected and automated vehicles (CAVs) are becoming widely diffused as road transport technology increasing road capacity by improving road safety and reducing pollution (Elvik, 2020). Regarding the connected automated transport systems (CATS), automated shuttle bus services are expected to be the first to align with their large scale business cases and will increase urban transport activities making transit systems more attractive to passengers. Several studies emphasized the advantages and disadvantages of automation in transport (Moreno et al., 2018; Paddeu et al., 2019; Blas et al., 2020; Ivanov et al., 2020), while many researches are investigating on qualifying the weaknesses and probable failures of automation and on increasing trust, comfort and road safety.

More specifically, automation is expected to improve traffic flows by increasing network capacity (Litman, 2014). The increased road capacity causes less traffic congestion and also offers decreased travel times (Pinjari et al., 2014; Heinrichs & Cyganski, 2015). In addition, the increase in capacity is significantly related to the market penetration rate of CAVs as well as the CAV parameters (Ye & Yamamoto, 2018a; 2018b). The introduction of CAVs will increase the throughput of highway facilities and improve traffic flow stability (Mahmassani, 2016; Talebpour & Mahmassani, 2016). Regardless of traffic impacts, autonomous vehicles are expected to decrease emissions. The operation of autonomous on-demand mobility services are projected to improve emissions by proposing more energy-efficient solutions (Greenblatt & Saxena, 2015a) even if the total distance travelled and average speed are increased (Greenblatt & Saxena, 2015b). Lastly, research conducted by Ge et al. (2018) showed that both safety and energy efficiency could be improved in the mixed flow through a validation of CAV design among conventional vehicles. Overall, there are several potential benefits of autonomous vehicles with respect to road safety, congestion as well as travel (Fagnant & Kockelman (2015).

Research related to user acceptance have shown high levels of trust and comfort for automated shuttle services (Eden et al., 2017; Nordhoff et al., 2019). Furthermore, public transit services encourage vehicle sharing, and improve walking and bicycling conditions (Lovejoy et al., 2014). In addition, ride-sharing increases the total number of rides served by CATS (Alonso-Mora et al., 2017) by merging several trips, reducing emissions (Shaheen et al., 2018, Shaheen and Cohen, 2019) and traffic volume (Alonso-Mora et al., 2017; Lokhandwala & Cai, 2018). On the contrary, shared-ride services provide less accessibility and comfort to the passengers, as the trip duration is longer due to the stops (Litman, 2020). In the case of CityMobil2 project, the introduction of autonomous public transit services, caused public reactions until the passengers could use the shuttle bus service and changed their opinion (Alessandrini et al., 2015).

Through simulation approaches, Talebpour et al. (2017) investigated the effects of reserved lanes for CAVs and found that if CAVs use dedicated lanes, congestion will be improved and their performance will be better than other policies. Similar research showed that mixed conditions policies could succeed higher capacity than the segregation of CAVs with conventional vehicles (Chen et al., 2017). In addition, several multiple simulation models have been developed and applied for designing and testing autonomous shuttle bus services in terms of waiting, travel times and their effect on network capacity and traffic conditions as well

(Marczuk et al., 2015; Lima Azevedo et al., 2016; Lam, 2016; Zellner et al., 2016; Scheltes & Correia, 2017; Shen et al., 2018). In a study conducted by Gasper et al. (2018), in which pedestrians and traffic were simulated using the SUMO software, reduced travel times for the pedestrians were shown due to the introduction of a shuttle bus service operation.

The aim of the present study is to examine the impacts of different autonomous transit services on traffic, environment and safety in urban environment. Through a series of use cases and realization scenarios executed on the network of Athens, Greece, this research provides in-depth investigations for the impacts of CAVs on a network level. The microscopic simulation analysis method is selected and different scenarios were formulated using the Aimsun Next mobility modelling software. The microsimulation results are critically assessed through the use of key performance indicators related to traffic, environment and safety and are compared for each of the examined autonomous transit services to allow for several useful and informative conclusions to be drawn.

The paper is organized as follows: in the next section the methodology is presented, in which the microscopic simulation and the use cases specifications are described. Afterwards, the microsimulation results for each use case are presented to examine the impacts of the corresponding services. In the last section of the paper, a summary of the present research results and their comparison is included, while the key findings, proposals for further research and paper limitations are also presented.

2. Methodology

2.1 Microscopic Simulation

In the present research, the microscopic simulation method was selected to examine the impacts of CAVs and autonomous transit services mainly on traffic, environment and energy efficiency. More specifically, the main purpose of this methodology is to identify the impacts of the adoption of CATS on traffic, including travel times, flows, traffic emissions and road safety under several simulation scenarios and to evaluate the influence of different CAV penetration rates on a microscopic level. Microscopic simulation provides information related to individual vehicles by modelling traffic flows at a high level of detail (Ehlert & Rothkrantz, 2001). The simulation inputs concern data from various sources such as the network geometry, traffic volume and modal split.

The data exported by the microsimulation can provide an initial, descriptive estimation of several impacts. Each vehicle is tracked as it interacts with surrounding traffic as well as with the environment. Moreover, microscopic simulation is widely used to evaluate new traffic control and management technologies as well as performing analysis of existing traffic operations (Owen et al., 2000). Modelling traffic flows allows to simulate the driving of every vehicle inside the considered transport network and provide many traffic-related impacts, while the traffic characteristics are taking into account that leads to estimate emissions with higher accuracy, as well (Zhu et al., 2017; Lopez et al., 2018). In addition, many studies have used the microsimulation method in order to analyze traffic conflicts and present the sequence of events with the causative factors of conflicts (Young et al., 2014).

2.2 Use Cases

Different scenarios were formulated using the Aimsun Next mobility modelling software in the Athens network. There are three use cases in the present study that concerned three different automated public transit services that were implemented, namely:

i) a point-to-point automated shuttle bus service connecting two modes in a small-scale network (part of the city of Athens) shown in Figure 1,
ii) a point-to-point automated shuttle bus service connecting several points in a large-scale network (the entire city municipality of Athens) shown in Figure 2,
iii) an on-demand mobility automated shuttle service in a large-scale network (the entire city municipality of Athens) shown again in Figure 2.

The two study models include data for each road segment that concerned geometric as well as functional characteristics namely length, width, number of lanes, directions, free-flow speed and capacity. In addition, the respective characteristics of nodes were also included in the model network: allowed movements, number of lanes per movement, priority, traffic light control plans, free speed flow and capacity.

The small-scale study network comprises a part of the city of Athens as shown in Figure 1 (left). This network was simulated in the Aimsun Next mobility modelling software is presented in Figure 1 (right) and consists of 158 nodes and 356 road segments. In addition, the total length of road sections is 70 km and the network size reaches approximately 3 km^2. In addition, the OD matrices consisted of 58×59 centroids of the study network and a total number of 27,500 car trips and 5,990 truck trips for a peak hour. Furthermore, the Athens model included 14 buses and 1 trolley line and 150 public transport stations as well as service frequencies and waiting times at stops.

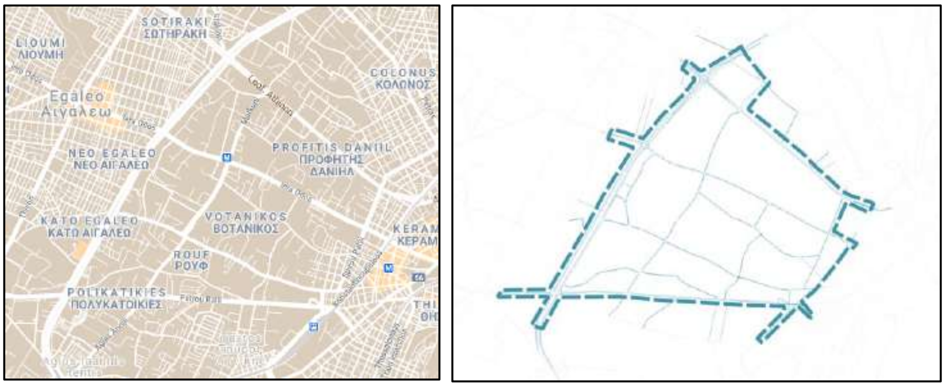

Figure 1: *Small-scale network in a conventional map (left) and in the Aimsun software (right)*

The large-scale study network comprises the city center of Athens as shown in Figure 2 (left). This network was also simulated in the Aimsun Next mobility modelling software as presented in Figure 2 (right) and consists of 1,137 nodes and 2,580 road segments. In addition, the total length of road sections is 348 km and the network size reaches approximately 20 km^2. In addition, the OD matrices consisted of 290×292 centroids of the study network and a total number of 82,270 car trips and 3,110 truck trips for a peak hour. Furthermore, the Athens model included 95 bus and 14 trolley lines and 1,030 public transport stations as well as service frequencies and waiting times at stops.

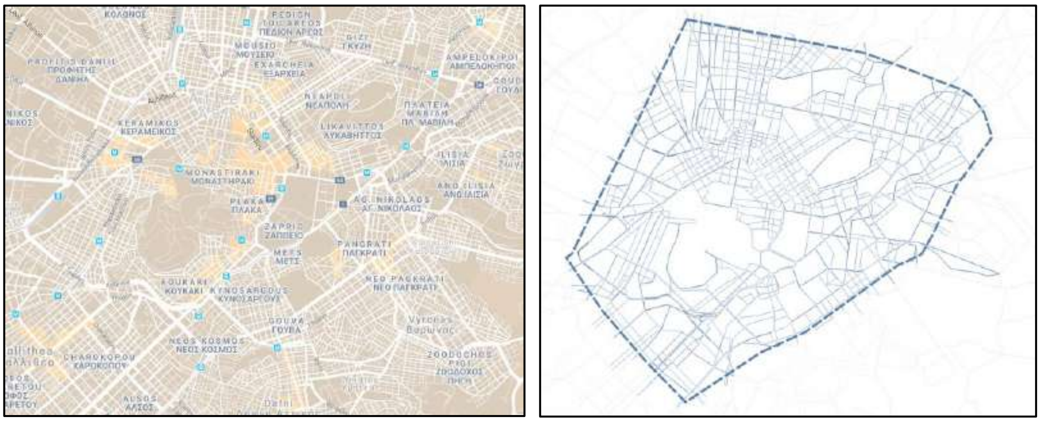

***Figure 2:** Large-scale network in a conventional map (left) and in the Aimsun software (right)*

For the first examined service, which is the point-to-point automated shuttle bus service connecting two modes in a small-scale network, one shuttle bus line was implemented in the network in order to connect two modes of transport. The shuttle buses connected the metro station “Eleonas” with the Athens intercity main bus terminal (Point A and point B respectively in Figure 3).

***Figure 3:** The first transit service’s bus line*

Aiming to provide a sufficient transport capacity for passengers, the service was considered to have four shuttle buses with total capacity of 10 passengers, in order to facilitate with higher service frequencies. Their dimensions were 5 meters length and 2.5 width. The max operating speed of the buses was 40 km/h, the mean speed 25 km/h. The frequency of the service was 15 minutes. The route included signalized arterials and secondary streets and its total length was 3.4 kilometers.

Overall for the first examined service, the following scenarios were formulated:

1) Baseline (no transit service operation)
2) Transit service operation in mixed traffic conditions during peak hour
3) Transit service operation using dedicated lane during peak hour
4) Transit service operation in mixed traffic conditions during peak hour while an incident occurs on the service route
5) Transit service operation in mixed traffic conditions during off-peak hour
6) Transit service operation using dedicated lane during off-peak hour.

In the scenario in which an incident occurred, a part of a road segment was blocked and the shuttle buses, as well as the surrounding traffic were forced to change lane and overtake the blocked segment.

For the second examined service, which is the point-to-point automated shuttle bus service connecting several points in a large-scale network, four shuttle bus lines were implemented in the city of Athens in order to complement the existing public transport as shown in Figure 4. The first shuttle bus line, Line 1, connects the metro station “Viktoria” (A) with the metro station “Panormou” (B), the second shuttle bus line, Line 2, connects the National Garden (A) and Greek Parliament with the National Archeological Museum (B), the third, Line 3, connects Omonoia Square (A) with Acropolis - Parthenon (B) and the fourth, Line 4, connects metro station “Rouf” (A) with the metro station “Neos Kosmos” (B).

***Figure 4:** The second transit service’s bus lines*

Aiming to provide a sufficient transport capacity for passengers, the service was considered to have sixteen shuttle buses with total capacity of 10 passengers, in order to facilitate with higher service frequencies. Their dimensions were 5 meters length and 2.5 width. The max operating speed of the buses was 40 km/h, the mean speed 25 km/h. The frequency of the service was 15 minutes. The total length of the shuttle bus service routes were 8 km (Line 1), 6 km (Line 2), 6 km (Line 3) and 8 km (Line 4).

Overall for the second examined service, the following scenarios were formulated:

1) Baseline (no transit service operation)
2) Transit service operation in mixed traffic conditions during peak hour
3) Transit service operation using dedicated lane during peak hour
4) Transit service operation in mixed traffic conditions during off-peak hour.

For the third examined service, traffic demand data for the city center of Athens were obtained through the Aimsun Next large-scale model and the output data of the optimization process was fed back into the Aimsun Next simulation. The optimization of the service's fleet was achieved externally, through a macroscopic, data driven approach, which consisted of two main steps. Firstly, we transformed the aggregated OD trip information for the city of Athens (Oikonomou et al., 2020) to disaggregated ride requests, by populating the OD trips into single trips in the same location and adding pickup and drop-off attributes to them, in order to portray the individuality of the calls both in the assignment and the routing stage. The disaggregated information was further considered as customers' requests for the on-demand service. In the second step, a Dial-a-Ride optimization Problem (DARP) was set-up and executed through Google's OR-Tools, without considering the attribute of time, and conducted along with an extensive sensitivity analysis in order to determine the service's final characteristics. The service's operation efficiency is demonstrated through a set of scenarios that vary in terms of the demand to be served, the fleet size and the vehicle capacity. The sensitivity analysis consisted of assigning percentages ranging from 1% to 100% of the total demand to the new service, for shuttle bus fleets with a proportionally increase on the number of vehicles, which had capacities of 1, 4, 8 or 15 passengers.

Finally, the scenarios of the third examined service that were selected to be examined extensively through the Aimsun software are the following:

1) Baseline (no transit service operation)
2) 5% of the total demand to be served by 50 autonomous shuttle buses of 8 passengers
3) 5% of the total demand to be served by 50 autonomous shuttle buses of 15 passengers
4) 10% of the total demand to be served by 100 autonomous shuttle buses of 8 passengers
5) 10% of the total demand to be served by 100 autonomous shuttle buses of 15 passengers.

In addition, in the traffic simulation model the shuttle buses characteristics were implemented. There were two types of shuttle buses that were examined. The dimensions of the first type, namely the one with a capacity of 8 passengers, was 4.5 meters in length and 2.5 meters in width and the dimensions of the second type, namely the one of 15 capacity, was 8 and 2.5 m, respectively. In addition, the max operating speed of the buses was 40 km/h and the mean speed 25 km/h and also were inserted in the model. For the on-demand operation scenarios, the existent public transport remained constant since the on-demand automated service was considered to be an additional service in the network.

It is noteworthy that the demand percentages include trips that were located exclusively inside the city center of Athens, as that is the most probable initial step of the implementation of such service (Maurer et al., 2016). The demand inflated centroids from the perimeter of the selected area of interest, the center of Athens, were omitted from the optimization process.

2.3 Modelling CAVs

Within the present research, two main driving profiles were simulated for modelling connected autonomous vehicles (CAVs), as in other studies (Sukennik, 2018; Mesionis et al., 2019), and are the following:

- 1st Generation (Cautious): limited sensing and cognitive ability, long gaps, early anticipation of lane changes and longer time in give way situations.
- 2nd Generation (Aggressive): advanced sensing and cognitive ability, data fusion usage, confident in making decisions, small gaps, early anticipation of lane changes and less time in give way situations.

The autonomous shuttle buses of the three services were simulated as 1st generation CAVs, since they were characterized as cautious and it was assumed that this profile was more appropriate for a public transport mode. Similarly, autonomous trucks were simulated as 1st generation CAVs, as well. In this study, all CAVs were assumed to be exclusively electric.

CAV lane-changing behavior was considered to be different than human driven vehicles' behavior. Hence, the Gipps lane changing model was applied (Gipps, 1986) that estimates the decisions before changing lane and ensures that vehicles behave logically in situations similar to real traffic conditions. All vehicle parameters that were used in the microsimulation are shown in Table 1.

Table 1: *Microsimulation CAVs parameters*

Factors			**Human Driven Vehicle**	**1st Generation CAV**	**2nd Generation CAV**
Max. acceleration		*Mean*	5.0	4.5	3.5
		Min	3.0	3.5	2.5
		Dev	0.2	0.1	0.1
		Max	7.0	5.5	4.5
Normal deceleration		*Mean*	3.4	4.0	3.0
		Min	2.4	3.5	2.5
		Dev	0.25	0.13	0.13
		Max	4.4	4.5	3.5
Max. deceleration		*Mean*	5.0	7.0	9.0
		Min	4.0	6.5	8.5
		Dev	0.5	0.25	0.25
		Max	6.0	7.5	9.5
Clearance		*Mean*	1.0	1.0	1.0
		Min	0.5	0.8	0.8
		Dev	0.3	0.1	0.1
		Max	1.5	1.2	1.2
Lane Changing Model	Overtake speed threshold		90%	90%	85%
	Look ahead distance	*Min*	0.8	1.1	1.0
		Max	1.2	1.3	1.25
	Safety margin	*Min*	1.0	1.0	0.75
		Max	1.0	1.25	1.0
Reaction time in car following (sec)			0.8	0.9	0.4

Regarding the implementation of CAVs, different penetration rate scenarios were simulated and are presented in Table 2. The cautious CAVs, since they were considered to be the first generation, appeared first in the scenarios and then followed by the aggressive CAVs until the last scenario, where only 2nd generation CAVs were included.

Table 2: *The CAV market penetration rate scenarios*

Type of Vehicle	A	B	C	D	E	F	G	H
Human-driven Car	100%	80%	60%	40%	20%	0%	0%	0%
1st Generation CAV	0%	20%	40%	40%	40%	40%	20%	0%
2nd Generation CAV	0%	0%	0%	20%	40%	60%	80%	100%
Human-driven Truck	100%	80%	40%	0%	0%	0%	0%	0%
Freight CAV	0%	20%	60%	100%	100%	100%	100%	100%

For each one of these scenarios, the different implementations of the three autonomous transit services were also simulated. Therefore, 112 scenarios were simulated in total (8 market penetration rate scenarios for each of the 6 point-to-point in a small-scale network, 4 point-to-point in a large-scale network and 4 on-demand in a large-scale network implementation scenarios). In addition, for each scenario, 10 different replications with random seeds generating stochastic results were simulated as well in order greater precision to be succeed. The simulation duration of each scenario was one hour and the simulation time step was 5 minutes.

3. Results

Through the microscopic simulation, the impacts of CAVs and the three different automated transit service implementation of 112 scenarios were extracted. The examined network-level impacts concerned traffic, environment as well as road safety. These impacts are the following and are presented in Figures 5, 6 and 7:

- Delay Time: mean delay time (sec/km),
- Distance Travelled: total distance travelled of the vehicles that exited the network (km),
- CO_2 Emissions: total CO_2 emissions (kg),
- NO_x Emissions: total NO_x emissions (kg),
- PM_{10} Emissions: total PM_{10} emissions (kg),
- Number of conflicts: total number of conflicts.

The environmental impacts obtained by the simulation using the Aimsun software, were calculated applying the formula developed by Panis et al. (2006). This model computes carbon dioxide (CO_2), nitrogen oxides (NO_X) and particulate matter (PM_{10}). In addition through simulation, the trajectories files of all scenarios were extracted and analyzed in the SSAM tool. This analysis provided the number of conflicts that occurred in the simulation scenarios and are shown in Figure 5, 6 and 7, as well.

3.1 Point-to-point automated shuttle bus service in a small-scale network

Simulation results concerned traffic, environment as well as road safety and are presented in Figure 5. Regarding the point-to-point automated shuttle bus service that connects two modes in a small-scale network, the traffic-related graphs illustrate that, if the shuttle bus drives on a dedicated lane, the delay time and total distance travelled remain the same during off peak hour for all mobility scenarios. In general, the existence of the shuttle bus service led to increased delays and total distance travelled for most market penetration scenarios. This can be explained by the fact that the service is considered as an additional service that complemented the existing public transport. Due to the high traffic volumes during peak hour, the existence of a dedicated lane significantly influenced the traffic conditions. More specifically in this scenario, increased delays as well as decreased travelled distances were noticed for multiple market penetration rate scenarios. As can be observed, automation decreased delay time during peak hour while during off peak remained constant. In addition, total distance travelled values did not seem to be significant affected when the number of autonomous vehicles was increased.

Concerning emissions, CO_2, NO_x and PM_{10} levels were all found to be significantly lower when the number of autonomous vehicles was increased. More specifically, CO_2, NO_x and PM_{10} emissions were increased for the shuttle service scenarios due to the appearance of autonomous vehicles, compared to the baseline scenario. In the rest of the market penetration rate scenarios when more autonomous vehicles were circulating within the network, the different implementation types of the automated shuttle bus service did not seem to have any significant differences for both peak and off peak scenarios.

In Figure 5, information about the number of conflicts during off peak and peak hour conditions is also visualized. In the peak hour graph, the number of conflicts presented a lot of oscilations. Overall, automation appears to decrease the number of conflicts during peak hour conditions except from the scenario in which an incident occurs. In this scenario, vehicles were forced to change lane more frequently in order to overtake the incident. In addition, in the 60% market penetration scenario, the number of conflicts was increased for the mixed and dedicated service scenarios. This finding can probably be explained by the mixed conditions when the second generation autonomous vehicles were introduced. In off peak hour conditions, the different implementation types of the automated shuttle bus service did not seem to present any significant differences between them.

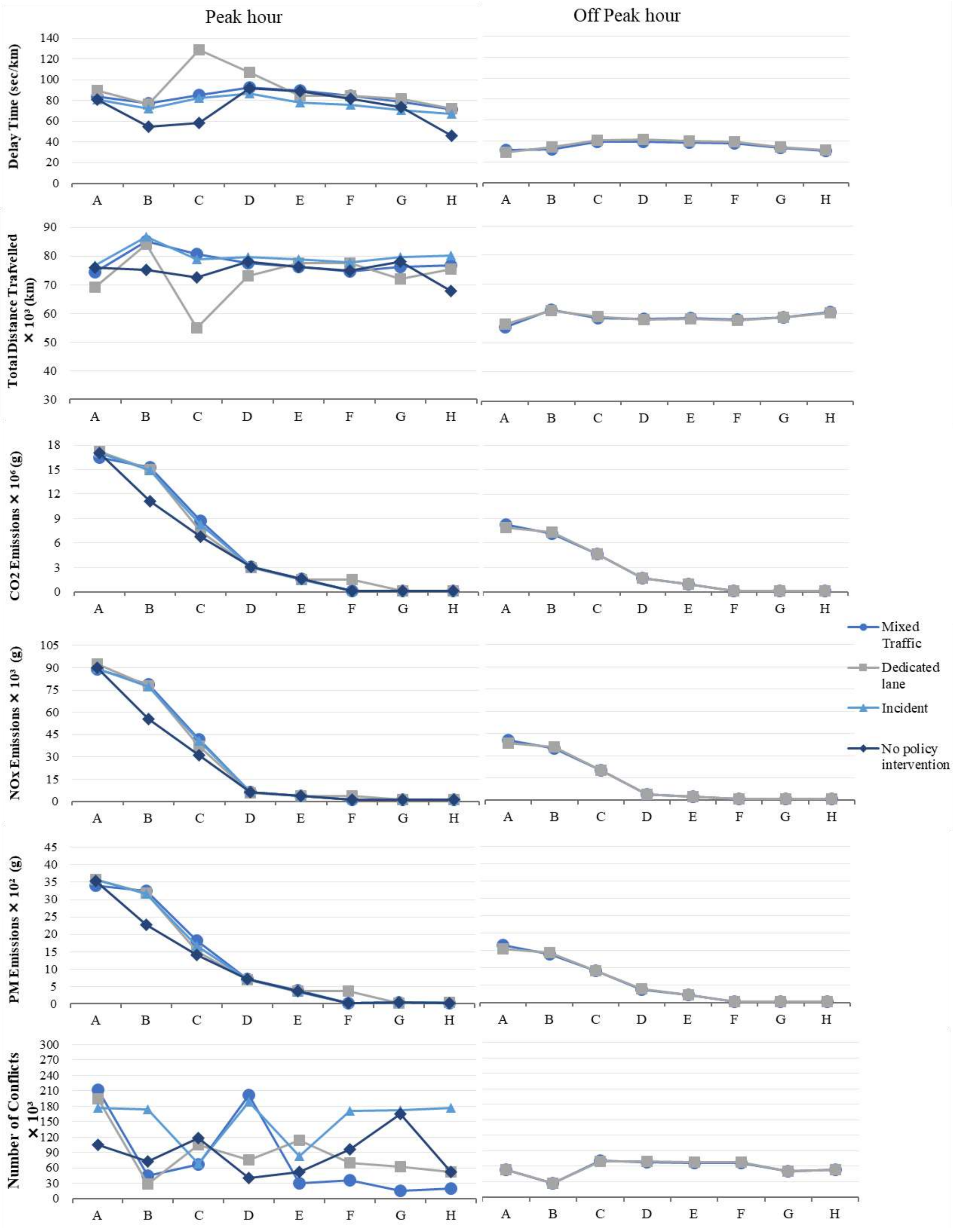

***Figure 5:** Point-to-point service on small-scale network level impacts for all simulation scenarios*

3.2 Point-to-point automated shuttle bus service in a large-scale network

The simulation results of the point-to-point automated shuttle bus service that operates in a large-scale network concerned traffic, environment and safety and are presented in Figure 6. If the shuttle bus is simulated to drive on a dedicated lane, delay time and total distance travelled remain the same for all mobility scenarios. In addition, the existence of the shuttle bus service did not significantly affect delays as well as total distance travelled for all market penetration scenarios. As can also be observed, automation decreased delay time during both peak hour and off peak hour conditions for the last two market penetration rate scenarios while the rest remained constant. Similarly, total distance travelled values seemed to be increased for the last two market penetration rate scenarios, as the traffic conditions were better and more vehicles finished their trips.

Concerning emissions, CO_2, NO_x and PM_{10} levels were significantly lower when the number of CAVs was increased. In addition, the different implementation types of the automated shuttle bus service did not seem to have any significant differences. Moreover, the number of conflicts during off peak and peak hour conditions are visualized. The number of conflicts was reduced when more autonomous vehicles existing the network during peak hour conditions and remained constant during off peak hour. Also it is noticed that, the number of conflicts was approximately the same for the different automated shuttle bus service scenarios.

3.3 Mobility on-demand automated shuttle service in a large-scale network

Simulation results of the mobility on-demand automated shuttle service that operates in a large-scale network are presented in Figure 7. Firstly, it seems that the implementation of the automated service led to decreased delay times. More specifically, delay time values of the baseline scenario were higher for all market penetration rates except from the last two, in which delay time was almost the same for all different types of the on-demand service implementation. In addition, the introduction of automation decreased delays. Regarding the total distance travelled it can be observed that, automation led to increased values for the last two scenarios, as the traffic conditions were better and more vehicles finished their trips, while for the rest of the scenarios there was a decrease. The on-demand service did not show any significant differences in total distance travelled.

Concerning emissions, the CO_2, NO_x and PM_{10} levels were significantly lower when the number of autonomous vehicles was increased. In addition, the different implementation types of the automated on-demand service did not seem to have any significant differences. The number of conflicts was reduced when more autonomous vehicles were existing in the network. Also it is revealed that, the number of conflicts was approximately the same for the different on-demand service scenarios.

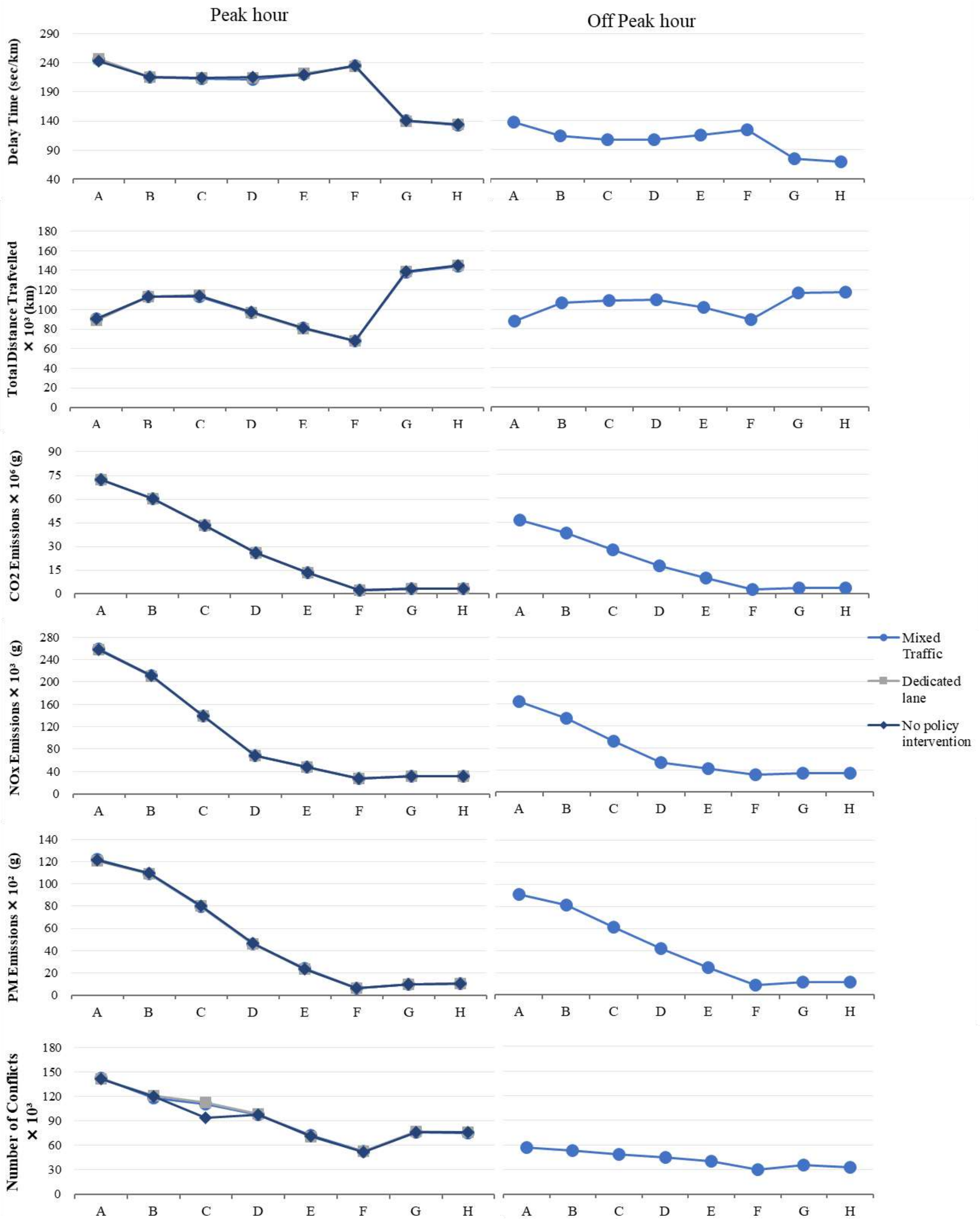

Figure 6: *Point-to-point service on large-scale network level impacts for all simulation scenarios*

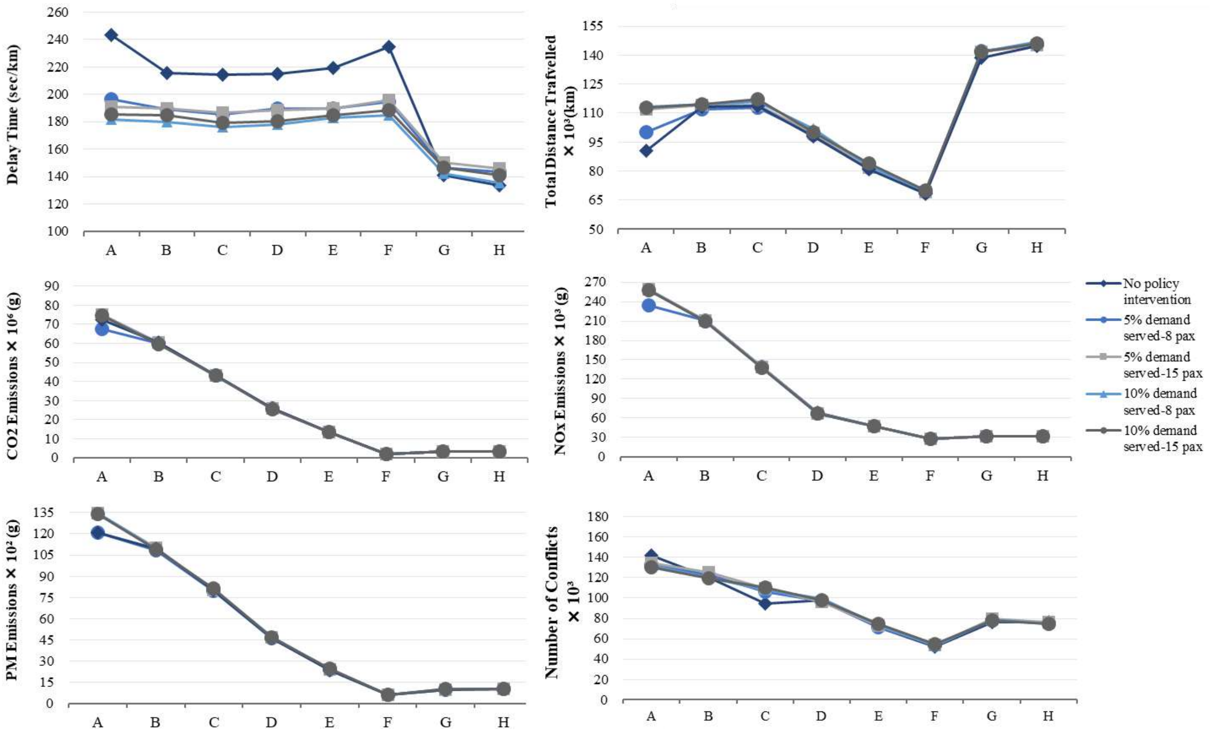

***Figure 7:** On-demand service on large-scale network level impacts for all simulation scenarios*

4. Conclusions

In the present research, the impacts of CAVs and the three different automated services implementation of 112 scenarios were extracted through microscopic simulation. The examined impacts on network level concerned traffic, environment, as well as road safety. A point-to-point automated shuttle bus service, that connects two modes in a small-scale urban network, led to increased delays and total distance travelled for the most of CAV market penetration rates. On the contrary, the point-to-point automated shuttle bus service that operates in a large-scale network did not significantly affect delays, as well as total distance travelled for all market penetration scenarios. In the other hand, the on-demand shuttle service in the same network showed decreased delay times and constant driven kilometers. Overall, if the shuttle buses of the point-to-point services drive on dedicated lanes, delay time and total distance travelled seem to remain approximately the same for all mobility scenarios, compared to the mixed traffic conditions.

In addition, the introduction of the different automated shuttle bus services did not significantly affect CO_2, NO_x and PM_{10} level, yet they were significantly lower when the number of autonomous vehicles was increased. Furthermore, the number of conflicts were not affected by the autonomous transit services implementation, except from the case when an incident occurred on the shuttle buses route. In a small-scale urban network, automation seemed to not affect traffic-related measurements, while in a large-scale urban network decreased delay times and increased total distance travelled values were noticed. The number of conflicts was also reduced when more connected and autonomous vehicles existed in the network.

The outcomes of the present research could enable passengers, drivers and stakeholders to assume a prepared and informed position in order to manage the autonomous public transit services in urban areas by using suitable strategies. The currently provided framework will be beneficial for future management of cities, as the modes of transport will be fundamentally affected due to the evolution of CATS and other forms of automation technology.

It is to note that the present study entails some limitations. Since the methodological approach is a microscopic simulation, assumptions regarding CAVs parameters and automated transit services operation have been made. Moreover, the acceptance of the examined transit services was not taken into account. Therefore, several pending issues remain open for future research to examine. Various impacts in relation to other or the examined automated services need to be further investigated, taking into account the particularities of different networks, vehicle types, automation levels, modes of transport and modal split issues.

Acknowledgements

The present research was carried out within the research project "LEVITATE - Societal Level Impacts of Connected and Automated Vehicles", which has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 824361.

5. References-Bibliography

Alessandrini, A., Campagna, A., Site, P. D., Filippi, F., & Persia, L. (2015). Automated vehicles and the rethinking of mobility and cities. *Transportation Research Procedia*, *5*(January 2016), 145–160. https://doi.org/10.1016/j.trpro.2015.01.002

Alonso-Mora, J., Samaranayake, S., Wallar, A., Frazzoli, E., & Rus, D. (2017). On-demand high-capacity ride-sharing via dynamic trip-vehicle assignment. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(3), 462–467. https://doi.org/10.1073/pnas.1611675114

Azevedo, C. L., Marczuk, K., Raveau, S., Soh, H., Adnan, M., Basak, K., Loganathan, H., Deshmunkh, N., Lee, D. H., Frazzoli, E., & Ben-Akiva, M. (2016). Microsimulation of demand and supply of autonomous mobility on demand. *Transportation Research Record*, *2564*(January), 21–30. https://doi.org/10.3141/2564-03

Blas, F., Giacobone, G., Massin, T., & Rodríguez Tourón, F. (2020). Impacts of vehicle automation in public revenues and transport equity. Economic challenges and policy paths for Buenos Aires. *Research in Transportation Business and Management*, *March*, 100566. https://doi.org/10.1016/j.rtbm.2020.100566

Chen, D., Ahn, S., Chitturi, M., & Noyce, D. A. (2017). Towards vehicle automation: Roadway capacity formulation for traffic mixed with regular and automated vehicles. *Transportation Research Part B: Methodological*, *100*, 196–221.

https://doi.org/10.1016/j.trb.2017.01.017

Eden, G., Nanchen, B., Ramseyer, R., & Evéquoz, F. (2017). *On the Road with an Autonomous Passenger Shuttle*. 1569–1576. https://doi.org/10.1145/3027063.3053126

Ehlert, P. A. M., & Rothkrantz, L. J. M. (2001). A Reactive Driving Agent for Microscopic Traffic Simulation. *Proceedings of the 15th European Simulation Multiconference (ESM2001)*, 943–949.

Elvik, R. (2020). The demand for automated vehicles: A synthesis of willingness-to-pay surveys. *Economics of Transportation*, *23*(June), 100179. https://doi.org/10.1016/j.ecotra.2020.100179

Fagnant, D. J., & Kockelman, K. (2015). Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations. *Transportation Research Part A: Policy and Practice*, *77*, 167–181. https://doi.org/10.1016/j.tra.2015.04.003

Gasper, R., Beutelschieß, S., Krumnow, M., Simon, L., Baksa, Z., & Schwarzer, J. (2018). *Simulation of Autonomous RoboShuttles in Shared Space*. *2*, 183–171. https://doi.org/10.29007/h58z

Ge, J. I., Avedisov, S. S., He, C. R., Qin, W. B., Sadeghpour, M., & Orosz, G. (2018). Experimental validation of connected automated vehicle design among human-driven vehicles. *Transportation Research Part C: Emerging Technologies*, *91*(September 2017), 335–352. https://doi.org/10.1016/j.trc.2018.04.005

Gipps, P. G. (1986). A model for the structure of lane-changing decisions. *Transportation Research Part B*, *20*(5), 403–414. https://doi.org/10.1016/0191-2615(86)90012-3

Greenblatt, J. B., & Saxena, S. (2015). Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. *Nature Climate Change*, *5*(9), 860–863. https://doi.org/10.1038/nclimate2685

Greenblatt, J. B., & Shaheen, S. (2015). Automated Vehicles, On-Demand Mobility, and Environmental Impacts. *Current Sustainable/Renewable Energy Reports*, *2*(3), 74–81. https://doi.org/10.1007/s40518-015-0038-5

Heinrichs, D., & Cyganski, R. (2015). Automated driving: How it could enter our cities and how this might affect our mobility decisions. *Disp*, *51*(2), 74–79. https://doi.org/10.1080/02513625.2015.1064650

Ivanov, S., Kuyumdzhiev, M., & Webster, C. (2020). Automation fears: Drivers and solutions. *Technology in Society*, *63*(October), 101431. https://doi.org/10.1016/j.techsoc.2020.101431

Lam, S. (2016). *A Methodology for the Optimization of Autonomous Public Transport* (Issue December 2016). https://doi.org/10.13140/RG.2.2.33767.91046

Litman, T. (2020). Autonomous Vehicle Implementation Predictions: Implications for Transport Planning. *Transportation Research Board Annual Meeting*, *42*(5 June 2020), 1–39.

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 Conference on Intelligent Transportation Systems, Proceedings, ITSC*, *2018-Novem*, 2575–2582. https://doi.org/10.1109/ITSC.2018.8569938

Lovejoy, K., Handy, S., & Boarnet, D. M. G. (2014). Impacts of Network Connectivity on Passenger Vehicle Use and Greenhouse Gas Emissions. *California Environmental Protection Agency-Air Resources Board*, *9*, 30.

Mahmassani, H. S. (2016). 50th Anniversary invited article autonomous vehicles and connected vehicle systems: Flow and operations considerations. *Transportation Science*, *50*(4), 1140–1162. https://doi.org/10.1287/trsc.2016.0712

Marczuk, K. A., Hong, H. S. S., Azevedo, C. M. L., Adnan, M., Pendleton, S. D., Frazzoli, E., & Lee, D. H. (2015). Autonomous mobility on demand in SimMobility: Case study of the central business district in Singapore. *Proceedings of the 2015 7th IEEE International Conference on Cybernetics and Intelligent Systems, CIS 2015 and Robotics, Automation and Mechatronics, RAM 2015*, 167–172. https://doi.org/10.1109/ICCIS.2015.7274567

Maurer, M., Gerdes, J. C., Lenz, B., & Winner, H. (2016). Autonomous driving: Technical, legal and social aspects. *Autonomous Driving: Technical, Legal and Social Aspects*, 1–706. https://doi.org/10.1007/978-3-662-48847-8

Mesionis, G., Roca, J., & Brackstone, M. (2019). *MODELLING CAVS ON THE UK S MOTORWAY NETWORK OUTPUTS FROM THE HUMANDRIVE PROJECT - PDF Free Download.pdf*. *2014*, 1–18.

Moreno, A. T., Michalski, A., Llorca, C., & Moeckel, R. (2018). Shared Autonomous Vehicles Effect on Vehicle-Km Traveled and Average Trip Duration. *Journal of Advanced Transportation*, *2018*. https://doi.org/10.1155/2018/8969353

Nordhoff, S., de Winter, J., Payre, W., van Arem, B., & Happee, R. (2019). What impressions do users have after a ride in an automated shuttle? An interview study. *Transportation Research Part F: Traffic Psychology and Behaviour*, *63*, 252–269. https://doi.org/10.1016/j.trf.2019.04.009

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 2020*. https://doi.org/10.1109/ITSC45102.2020.9294576

Owen, L. E., Zhang, Y., Rao, L., & McHale, G. (2000). Traffic flow simulation using *CORSIM*. *Winter Simulation Conference Proceedings*, *2*, 1143–1147. https://doi.org/10.1109/WSC.2000.899077

Paddeu, D., Calvert, T., Clark, B., & Parkhurst, G. (2019). *New Technology and Automation in Freight Transport and Handling Systems Future of Mobility : Evidence Review*. 59.

Panis, L. I., Broekx, S., & Liu, R. (2006). Modelling instantaneous traffic emission and the influence of traffic speed limits. *Science of the Total Environment*, *371*(1–3), 270–285. https://doi.org/10.1016/j.scitotenv.2006.08.017

Pinjari, A. R., Augustin, B., & Menon, N. (2014). *Highway Capacity Impacts of Autonomous Vehicles: An Assessment*. *813*, 68–70.

Scheltes, A., & de Almeida Correia, G. H. (2017). Exploring the use of automated vehicles as last mile connection of train trips through an agent-based simulation model: An application to Delft, Netherlands. *International Journal of Transportation Science and Technology*, *6*(1), 28–41. https://doi.org/10.1016/j.ijtst.2017.05.004

Shaheen, S., & Cohen, A. (2018). Is it time for a public transit renaissance?: Navigating travel behavior, technology, and business model shifts in a brave new world. *Journal of Public Transportation*, *21*(1), 67–81. https://doi.org/10.5038/2375-0901.21.1.8

Shaheen, S., & Cohen, A. (2019). Shared ride services in North America: definitions, impacts, and the future of pooling. *Transport Reviews*, *39*(4), 427–442. https://doi.org/10.1080/01441647.2018.1497728

Shen, Y., Zhang, H., & Zhao, J. (2018). Integrating shared autonomous vehicle in public transportation system: A supply-side simulation of the first-mile service in Singapore. *Transportation Research Part A: Policy and Practice*, *113*(July), 125–136. https://doi.org/10.1016/j.tra.2018.04.004

Sukennik, P. (2018). *Micro-simulation guide for automated vehicles*. *723201*, 1–29.

Talebpour, A., & Mahmassani, H. S. (2016). Influence of connected and autonomous vehicles on traffic flow stability and throughput. *Transportation Research Part C: Emerging Technologies*, *71*, 143–163. https://doi.org/10.1016/j.trc.2016.07.007

Talebpour, A., Mahmassani, H. S., & Elfar, A. (2017). Investigating the effects of reserved lanes for autonomous vehicles on congestion and travel time reliability. *Transportation Research Record*, *2622*(1), 1–12. https://doi.org/10.3141/2622-01

Ye, L., & Yamamoto, T. (2018a). Impact of dedicated lanes for connected and autonomous vehicle on traffic flow throughput. *Physica A: Statistical Mechanics and Its Applications*, *512*, 588–597. https://doi.org/10.1016/j.physa.2018.08.083

Ye, L., & Yamamoto, T. (2018b). Modeling connected and autonomous vehicles in heterogeneous traffic flow. *Physica A: Statistical Mechanics and Its Applications*, *490*(2018), 269–277. https://doi.org/10.1016/j.physa.2017.08.015

Young, W., Sobhani, A., Lenné, M. G., & Sarvi, M. (2014). Simulation of safety: A review of the state of the art in road safety simulation modelling. *Accident Analysis and Prevention*, *66*, 89–103. https://doi.org/10.1016/j.aap.2014.01.008

Zellner, M., Massey, D., Shiftan, Y., Levine, J., & Arquero, M. J. (2016). Overcoming the Last-Mile Problem with Transportation and Land-Use Improvements: An Agent-Based Approach. *International Journal of Transportation*, *4*(1), 1–26. https://doi.org/10.14257/ijt.2016.4.1.01

Zhu, W. X., & Zhang, J. Y. (2017). An original traffic additional emission model and numerical simulation on a signalized road. *Physica A: Statistical Mechanics and Its Applications*, *467*, 107–119. https://doi.org/10.1016/j.physa.2016.10.009