Impacts of Autonomous Shuttle Services on Traffic, Safety and Environment for Future Mobility Scenarios

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***Abstract*—In the era of automation, autonomous point – to – point shuttles are said to be among first mobility on demand service that will emerge. But, what will be the impacts of such a service in the implementation area? The scope of the present paper is to assess the impacts of an autonomous shuttle bus service on traffic conditions, road safety and environment. For this purpose, a shuttle bus route was designed to operate in a part of the Athens road network and various scenarios have been developed including peak and off peak hours, existence of a dedicated lane for the shuttle bus, incident occurrence as well as different penetration rates and profiles of autonomous vehicles. Results indicate that the autonomous shuttle bus operation leads to increased delay times on its route. The speed variance of shuttle bus and the prevailing traffic vehicles is up to 25 km/h during off peak hour. It is also shown that if the shuttle bus uses a dedicated lane, both the delay time and CO2 emissions are decreased. Automation decreases CO2 emissions during peak hour conditions and improves road safety, as the number of conflicts is reduced.**

I. Introduction

The number of autonomous vehicles is expected to gradually increase within the next years. This new technology and its components will govern in all transportation sectors - road, rail, maritime and aviation – while drivers, passengers and users should be ready for their advent. Many studies have revealed the advantages and disadvantages of automation in transport. Researchers, engineers and car manufacturers are continuously and intensively working for alleviating the drawbacks and potential failures that the automation may bring and ensure comfort and safety for the drivers and the users.

Concerning road sector, the automation will not only refer to private passenger cars, but also to public transportation. One of the modes that will be influenced by the automation technology and the various functions are the shuttle busses where driverless mini busses will transfer passengers from one point to another. Shuttle services widely exist worldwide serving transfer and connection purposes for medium and short distances. Autonomous shuttles and more specifically the electric ones, are expected to reduce operational costs while increasing ridership [1], as well as costs related to fuel consumption and driver employment [2]. Real time experiments and simulation tests or surveys have been conducted worldwide in order to reveal and assess the impacts of autonomous shuttle bus on traffic conditions, safety and environment in order to make them more attractive to riders.

The issue of scheduling autonomous shuttle busses was investigated by [3] who applied the deficit function for skip-stop and departure time optimization based on real time passenger demand. Low speed autonomous vehicle and shuttles have been analyzed in terms of their behavior in crowded areas and their interaction with vulnerable road users by applying the collision avoidance algorithm [4-6], based on real world conditions or simulation studies. Low speed shuttles have also been analyzed in [7] and [8] for on demand services while [9] and [10] proposed an architecture for automated driving using passenger cars and an autonomous electric shuttle.

There are many projects concerning the use of autonomous shuttles for transit purposes, such as Park Shuttle I and II for transferring people from a car park to the airport of Amsterdam and within Rivium Business Park in Rotterdam respectively [11-14]. Both projects revealed the efficiency of autonomous shuttles as well as their attractiveness as a large number of people are using them on daily basis. The same results were achieved by the use of small autonomous vehicles for connecting Heathrow Airport in London with the business car park within the CityMobil European Project (City Mobil European Project). Autonomous shuttles exist also in Vegas, USA [15]. Small automated cars for people or good transfer were designed within the framework of CyberCars and CyberCars2 projects offering door-to door and on demand services [16-17]. Within the framework of the Railcab project, an autonomous shuttle system was developed based on on-demand scheduling providing both passenger and goods transfer [18-20]. The autonomous on demand services in public transportation has also been investigated in [8] and [21].

The interaction between RoboShuttles and pedestrians has been modeled and simulated in SUMO by modelling a multi modal trip of pedestrians where they walk, board on the nearest RoboShuttle and disembark. The results showed that there is a reduction in travel times for the pedestrians when the pedestrian traffic is low [22]. Apart from SUMO, agent – based models have also been developed and applied for designing and testing autonomous shuttle services [23 -28], in terms of waiting and travel times as well as their effect on road capacity and traffic conditions.

Finally, many surveys have been conducted for revealing the perception of passengers after using autonomous shuttles. In Finland, one third of the participants felt safer in the shuttle than in conventional busses, but they were concerned about the in-vehicle security and the emergency management [29]. Familiarity with this type of transport mode was also found to be an important factor towards acceptance of autonomous functions [30], [31] along with the need for better communication between the autonomous vehicle and the other road users [30]. High service quality has been found to be an

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important factor in accepting autonomous shuttles [32] compared to the low speed which could be a deterrent factor [32,33]. Finally, user enjoyment, benefits from autonomous shuttle use, resources available [34], perceived usefulness and first experience with autonomous shuttle [35] influence their acceptability and the behavioral intention to use such a transport mode. The human perception and interactions were also investigated within the framework of the CATS project [36].

The aim of this paper is to assess the impacts of autonomous shuttle services in traffic, road safety and environment at the emergence of the service both at current traffic conditions and in future traffic conditions. For this we introduce a point to point shuttle service in a part of the Athens road network and we test its impacts including peak and off peak hours, existence of a dedicated lane for the shuttle bus, incident occurrence as well as different penetration rates and profiles of autonomous vehicles. The results are discussed with respect to specific key performance indicators that reflect the impact of the service to traffic, safety and environment.

The remainder of the paper is organized as follows: the methodological approach used for introducing the AV and the shuttle service to simulation is presented, then the use cases and the different scenarios of future autonomous traffic conditions are discussed. The simulation results are then presented. The paper ends with a discussion on the results and possible future research directions.

II. Implementing Autonomous Vehicles in Simulation

To analyze autonomous vehicles, we implement them in the microscopic simulation environment of AIMSUN software. The behavior of the autonomous shuttle bus will be modelled based on the joint consideration of the Cooperative adaptive cruise control (CACC) and the Gipps model (which are explained in the next section), different scenarios will be developed and applies in the simulation and the impact of the public transport mode will be assessed in terms of safety, traffic and environment.

The Gipps's model is a car following model developed by Gipps [37] analyzing the behavior and response of the following vehicle based on the driver's actions of the preceding vehicle. The model has been widely used for many purposes and applications [38] like highway traffic analysis [39] in microscopic simulation software like AIMSUN [40, 41], SIGSIM [42], and MULTISIM [43] while many researchers have tried to develop different calibration methods [44-48]. The basic formula of the Gipps's car following model:

$$\upsilon_n(t+\tau) = \min\{\upsilon_n(t) + 2.5\alpha_n\tau(1- \upsilon_n(t)/V_n)(0.025+ \upsilon_n(t)/V_n)^{1/2},$$
$$b_n\tau + (b_n^2\tau^2 - b_n [2[x_{n-1}(t) - s_{n-1} - x_n(t)] - \upsilon_n(t)\tau - \upsilon_{n-1}(t)^2/b])^{1/2}\} \quad (1)$$

where υ is the speed of each vehicle, α the maximum acceleration, τ the reaction time, V the wished speed, bn the most severe braking, s the effective size of the vehicle and x the vehicle position.

For modelling the autonomous vehicles in AIMSUN software, the Cooperative Adaptive Cruise control model (CACC) was used. CACC is an enhancement of the ACC model and is based on V2V communication. The following vehicle obtains access to the acceleration, speed and position of the preceding vehicle for adopting its speed and acceleration accordingly. Various CACC logics and applications have been developed and reported in the literature [49-55]. According to [49] the acceleration of the following vehicle when CACC logic is applied is given from the following formula:

$$\alpha_{ref\_}d = k_\alpha\alpha_p + k_v(v_p-v) + k_d(r-r_{ref}) \quad (2)$$

where α is the acceleration of the following vehicle, k_α is the acceleration gain, k_v is the speed gain and k_d the distance gain.

Finally, the lane changing model applied in the present research is the one developed by Gipps [56] and it describes the decisions a driver has to make in order to perform a lane change based on the prevailing conditions. According to Gipps model, the driver will perform a lane change if the criteria of necessity, desirability and possibility are fulfilled. The main parameters when applying the lane changing model in AIMSUN are:

1. The distance zone factor used to modify the three distance zones defined in the lane changing model representing driver's behavior during the lane changing process.

2. The overtake speed threshold below which the driver will consider to overtake.

3. Lane recovery speed threshold above which a vehicle will decide to get back into the adjacent slower.

4. The aggressiveness level which allows vehicles to accept shorter gaps.

5. The cooperation in creating gap between the vehicles.

III. The Use Case

We implement a point to point automated shuttle service in Athens Network in AIMSUN. The study network is a part of the city of Athens, which consists of 728 nodes and 1636 sections. The shuttle bus connects the metro station "Eleonas" with the Athens intercity main bus terminal (Point A and point B respectively in Figure 1).

Figure 1. Shuttle bus route

The shuttle bus is considered to have a total capacity of 10 passengers. Its dimensions are 5 meters length and 2.5 width. The max operating speed of the bus is 40.0km/h, the mean speed 25.0km/h. The frequency of the service is 15 minutes. The shuttle bus route connects the metro station "Eleonas" (A) with the Athens intercity bus terminal (B) as shown in Figure 1. The route includes signalized arterials and secondary streets and its total length is 3.4 kilometers. The shuttle service scenarios include peak and off peak hour traffic conditions, the use of a dedicated lane and an incident condition on the shuttle bus route. One of the existing lanes was converted to a dedicate lane for the shuttle service aiming to assess the impact of this strategy without changing the road geometry.

Shuttle Bus and Surrounding Vehicles Specifications

Two main driving profiles for autonomous vehicles have been used in microscopic simulation studies [57], [58]:

- Cautious: long clearance in car-following, long anticipation distance for lane selection, long clearance in gap acceptance in lane changing, limited overtaking, long gaps.
- Aggressive: short clearance in car-following, short anticipation distance for lane selection, short clearance in gap acceptance in lane changing, limited overtaking, no cooperation, small gaps.

In this work, the shuttle bus is modeled as a cautious AV profile, as a cautious driving is considered more appropriate for a public transport service. Moreover, a cautious AV driving is still more aggressive than human driving.

The surrounding vehicles are also distinguished by multiple profiles seen in Table I. The purpose of intermediate profiles is to normalize the appearance of automation in traffic. Two cautious profiles are created, Profile 1 is more similar to a Human driven vehicle and Profile 2 more similar to a cautious AV. The second profile and the cautious AV profile have also connectivity. The parameters of the car following model and the lane changing model along with their values used within this research study are also presented in Table I.

TABLE I. VEHICLE PARAMETERS

Models	**Factors**		**Human Driven Vehicle**	**Cautious AV**				
				Profile 1	***Profile 2***	***Profile 2 conne-cted***	***Cautious AV***	***Cautious AV-conne-cted***
	Safety Margin		1.0	1.25	1.75	1.75	2.0	2.0
Car Following Model	Sensitivity	*Mean*	1.0	1.3	1.4	1.4	1.5	1.5
		Min	1.0	1.0	1.1	1.1	1.1	1.1
		Max	1.0	1.5	1.8	1.8	1.9	1.9
	Vehicles Equipped with CACC:		0%	0%	0%	100%	0%	100%
Lane Changing Model	Overtake Speed Threshold:		90%	90%	85%	85%	85%	85%
	Cooperate in Creating a Gap:		YES	YES	NO	NO	NO	NO
	Distance Zone	*Min*	0.8	0.9	1.15	1.15	1.25	1.25
		Max	1.2	1.3	1.4	1.4	1.5	1.5

The critical parameters taken into account in the traffic models, along with their typical values are the following [58], [59]:

- Safety Margin Factor: A factor which determines when a vehicle can move at a priority junction. A common value for human drivers is 1.
- Sensitivity Factor: The parameter which control the clearance distance. Value for human behaviour is 1.
- Vehicles equipped with CACC: The percentage of connected vehicles.
- Overtake speed threshold: The percentage of the desired speed of a vehicle which decides to overtake. A common value for human drivers is 90%.
- Cooperate in Creating a Gap: If there is collaboration between drivers. The human behaviour is yes.
- Distance Zone Factor: The factor which determines where vehicles consider their lane choice for a forthcoming. A common value for human drivers is a distribution between 0.8 and 1.2.

IV. FUTURE MOBILITY SCENARIOS

The impact assessment of the shuttle bus service is analyzed for the horizons 2021 and 2040 and for each one different scenario for autonomous vehicles penetration rate in the prevailing traffic are developed. These scenarios are:

- No automation scenario: no automated vehicles are considered.
- Pessimistic scenario: low percentages of autonomous and connected vehicles are considered.
- Neutral scenario: high percentages of autonomous vehicles and low of connected vehicles are considered.
- Optimistic scenario: high percentages of autonomous and connected vehicles are considered.

The connectivity is taken into consideration only in the future mobility scenarios for the year 2040. The penetration rates of the different vehicle profiles per future mobility scenario are presented in Table II. It is to note that, all scenarios include fossil engine and electric cars, based on the existing electromobility technology. In the future, the Level 0-2 fossil engine cars will be decreased, but the number of electric cars will be increased.

TABLE II. PENETRATION RATES OF THE DIFFERENT VEHICE PROFILES

Vehicle profiles	**No Automation**		**Pessimistic Scenario**		**Neutral Scenario**		**Optimistic Scenario**	
	2021	***2040***	***2021***	***2040***	***2021***	***2040***	***2021***	***2040***
Car Levels 0-2 fossil fuel engine	94%	68%	93%	48%	92%	31%	91%	14%
Car Levels 0-2 electric	6%	32%	6%	22%	7%	19%	7%	11%
Cautious AV Profile 1	0%	0%	1%	9%	1%	15%	2%	23%
Cautious AV Profile 2	0%	0%	0%	8%	0%	10%	0%	15%
Cautious AV Profile 2 - connected	0%	0%	0%	4%	0%	10%	0%	15%
Cautious AV	0%	0%	0%	6%	0%	8%	0%	11%
Cautious AV - connected	0%	0%	0%	3%	0%	8%	0%	11%

V. RESULTS

A. Impacts on the shuttle bus route

For investigating the impacts of the shuttle bus service on its route only the horizon 2021 was considered and four scenarios were developed. The first two scenarios simulated traffic conditions with no shuttle bus service during peak and off peak hour. The other two scenarios include the shuttle bus service and the analysis is conducted again for both off peak and peak hour. The results for the different scenarios are presented in Table III and the street is also considered.

TABLE III. NO VERSUS SHUTTLE SERVICE IMPACTS

Traffic condition	Street type	Speed variance (km/h)	Delay Time (sec/km)			CO2 Emission (kg)		
			No Shuttle service	***Shuttle service***	***Change***	***No Shuttle service***	***Shuttle service***	***Change***
Peak hour	Signalized Arterial	34	130	130	0%	476.6	487.9	2%
	Secondary Street	13	246	252	2%	672.7	729.8	8%
Off Peak hour	Signalized Arterial	45	8	14	63%	256.1	318.4	24%
	Secondary Street	26	8	10	24%	135.5	132.8	-2%

Table III results show that the speed variance of the Shuttle bus gets higher values during off peak hour than peak hour. These results can be explained due to the increased traffic volumes during the peak hour. Additionally, the speed variance is higher when the shuttle bus is on signalized arterial street due to the higher speed limits. It is to note that values of speed difference over 20km/h can be related to increased accident risk in the road section this speed difference is observed.

Concerning the traffic impacts, the operation of the shuttle bus leads to increased delays. More specifically, during off peak hour, the delay time is increased by 63% and 24% for signalized arterials and secondary streets respectively. The shuttle bus has a minor impact on delays during peak hour, as only a slight increase of 2% on the secondary streets is observed. It seems that the shuttle bus service affects traffic only during off peak hour, when the traffic is much lower and stochastic.

Finally, the analysis showed that shuttle bus operation causes an increase of 2% and 8% in CO2 emissions, during peak hour for the signalized arterial and secondary street respectively. During off peak, the signalized arterials are burdened with an increase of 24% while on the secondary streets a decrease of 2% is observed. That probably happened because shuttle bus service causes traffic congestion.

B. *Network Level Impacts*

For investigating the impacts of the shuttle bus service on network level, forty scenarios were developed, simulated and analyzed that differ in terms of:

- The horizon of the analysis (2021, 2040).
- The period of the day (peak/off peak hour).
- The mobility scenarios (no automation, pessimistic, neutral, optimistic).
- The percentage of the different types of vehicles in traffic, dedicated lane, incident occurrence.

Results concerning delay time, CO2 emission and total conflict change are summarized in Table VI. For the calculation of the number of conflicts the SSAM tool is applied on the data obtained from simulation trajectory files. Table IV illustrates that, if the shuttle bus drives on a dedicated lane, the delay time is increased during peak hour and remains the same during off peak hour for all mobility scenarios. Due to the high traffic volumes during peak hour, the existence of a dedicated lane does not significantly influence the traffic conditions. Similarly, the incident occurrence does not seem to affect delay values. Concerning emissions, the dedicated lane scenario results in higher CO2 levels for all mobility scenarios and both peak and off peak hour conditions.

Incident conditions leads to higher levels of CO2 emissions, when the percentage of autonomous vehicles is low. Automation seems to decrease the number of conflicts during peak hour condition as in 2040 the conflicts for the optimistic scenario are decreased by 6%, 8% for the scenarios with and without a dedicated lane respectively, and by 13% when an incident occurs. In 2021, automation increases the number of conflicts, when shuttle bus uses a dedicated lane. This can be explained due to the reduced capacity caused by the use of a dedicated lane and the practically non-existent automation in 2021 compared to 2040. However, for incident conditions, automation decreases the number of conflicts for all future mobility scenarios and both 2021 and 2040.

In relation to the type of conflicts, automation seems to lead to decreased numbers of rear end conflicts for both peak and off-peak hour scenarios. On the other hand, it seems that if the shuttle bus uses a dedicated lane, the number of lane change conflicts is higher. Finally, the number of rear end conflicts is increased if an incident occurs on the shuttle bus route.

TABLE IV. SHUTTLE SERVICE SCENARIOS IMPACTS

Impacts	Scenarios		No Automation		Pessimistic		Neutral		Optimistic	
			2021	***2040***	***2021***	***2040***	***2021***	***2040***	***2021***	***2040***
Delay Time (sec/km)	Peak hour	*Mixed traffic*	75	92	72	100	73	127	74	101
		Dedicated lane	68	89	70	93	68	93	75	93
		Incident	75	95	71	95	73	91	71	99
	Off Peak hour	*Mixed traffic*	5	5	5	6	4	5	5	7
		Dedicated lane	6	7	6	7	6	8	6	8
CO2 Emission (kg)	Peak hour	*Mixed traffic*	11,287.5	12,075.2	10,625.8	10,889.0	11,303.0	10,613.3	11,157.4	11,237.6
		Dedicated lane	10,613.4	11,683.8	10,444.1	10,771.9	10,810.2	11,517.2	11,204.1	10,904.7
		Incident	11,746.3	12,557.4	10,816.5	10,662.5	11,284.7	11,614.8	11,035.3	11,261.2
	Off Peak hour	*Mixed traffic*	3,429.3	3,798.2	3,497.7	3,956.3	3,100.2	3,815.8	3,286.9	4,262.3
		Dedicated lane	3,244.9	3,754.0	3,239.2	3,809.9	3,213.2	3,947.9	3,341.5	3,998.0
Total conflict change (%)	Peak hour	*Mixed traffic*	-	-	-9%	-22%	-3%	-17%	1%	-6%
		Dedicated lane	-	-	17%	-17%	11%	-14%	46%	-8%
		Incident	-	-	-9%	-32%	0%	-21%	-5%	-13%
	Off Peak hour	*Mixed traffic*	-	-	30%	98%	-68%	-43%	-33%	152%
		Dedicated lane	-	-	-5%	-7%	-17%	-2%	5%	8%

In Figure 2 information about the delay time and CO2 emissions during off peak and peak hour conditions are visualized.

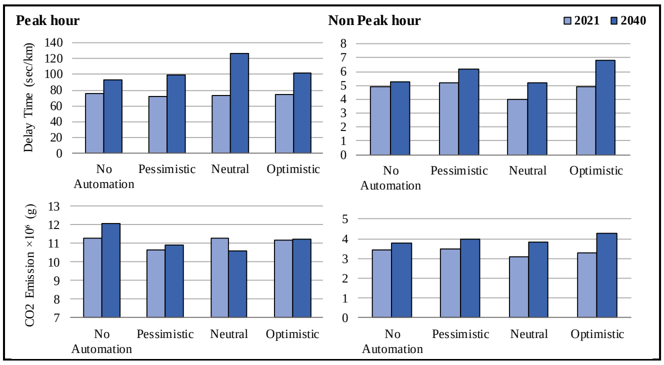

Figure 2. Delay Time and CO2 Emission on Peak and Off Peak hour

As can be observed, automation decreases delay time for both off peak and peak hour scenarios in 2021. However, in 2040 it seems that delay time is higher due to the increased number of autonomous vehicles in the prevailing traffic. Automation decreases the CO2 emissions during the peak hour, while the level of CO2 emissions remains the same during off peak.

VI. DISCUSSION AND CONCLUSION

The present paper studied the impacts of the introduction of an autonomous shuttle bus in an urban network on traffic, safety and environmental indicators. From the results of the analysis it was found that the autonomous shuttle bus leads to increased delay times on its route, especially on the signalized arterials because of the higher speed limits. Also, speed variance of shuttle bus and the prevailing traffic vehicles is up to 25 km/h during off peak hour, which means that the use of a dedicated lane is reasonable. The analysis of the dedicated lane scenario revealed that if the shuttle bus uses a dedicated lane, both the delay time and CO2 emissions are decreased during peak hour. An incident occurrence on the shuttle service route was not observed to affect traffic delays.

Automation decreases CO2 emissions during peak hour conditions, while no change in CO2 levels is observed during off peak hour. On the other hand, delay time gets higher values when more automated vehicles exist in the network. Nevertheless, automation improves road safety, as the number of conflicts is reduced. In 2040 the conflicts for optimistic scenario are decreased 6%, 8% and 13% during peak hour for the scenarios with and without a dedicated lane and incident occurrence, respectively. In addition, neutral scenario caused 17%, 14%, 21% reduction during peak hour and 21%, 43%, 2% reduction during off peak hour for the same scenarios, respectively.

Evidently in order for the results to be easily generalized to a city level further research is needed. Initially, more than one shuttle bus lines could be added in the city of Athens and investigate the impacts of a large-scale shuttle bus service in Athens. Moreover, since traffic conditions are expected to be mixed (legacy and autonomous vehicles) in the future, the impacts of drivers' behavior in the presence of automation and connectivity on the road network, in various urban contexts, should be investigated. Finally, the integration of autonomous shuttle services to the future transport system where multiple different mobility on demand services in a city network will operate may deserve further research. The concept of Autonomous On Demand Mobility is very promising in urban environments and research and investigation of policies and models are already under investigation. Automation favors the development of such new future mobility concepts that can be used both for passenger and freight transport.

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