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Impacts of automated driving vehicles on bus depot operation using naturalistic data

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Abstract

The EU SHOW project is conducting real-life demonstrations across 20 European cities to investigate the integration of Automated Driving (AD) vehicles into various schemes. One such demonstration site is the Madrid site, which concerns bus depot operations. The present study aims to support this real AD vehicles implementation by applying the microsimulation method in order to investigate their impacts that could not be measured in reality. Specifically, four scenarios were simulated: three involving three different AD vehicle operations and a baseline scenario without the AD vehicles. Results showed that AD vehicles led to increased bus depot delays and travel times, and decreased speed, since they keep lower speed than the human-driven vehicles that coexist in the depot. This simulation approach enables the assessment of potential alternatives before real-life interventions, guiding stakeholders and practitioners to prioritize essential aspects for future conditions, specifically AD vehicle operations.

Keywords: *Autonomous vehicles, Microscopic simulation, Naturalistic data, Impact assessment, Bus depot.*

Περίληψη

Μέσω του Ευρωπαϊκού έργου SHOW πραγματοποιείται η εισαγωγή αυτοματοποιημένων υπηρεσιών σε 20 ευρωπαϊκές πόλεις με σκοπό τη διερεύνηση της ενσωμάτωσης αυτής σε διάφορα συστήματα. Μία από τις πόλεις εφαρμογής είναι η πόλη της Μαδρίτης, στην οποία πραγματοποιείται η εισαγωγή αυτόνομων οχημάτων σε έναν σταθμό λεωφορείων. Η παρούσα μελέτη αποσκοπεί στην υποστήριξη αυτής της εισαγωγής αυτόνομων οχημάτων μέσω της πραγματοποίησης προσομοίωσης της κυκλοφορίας με σκοπό τη διερεύνηση των επιπτώσεών τους, οι οποίες δεν μπορούσαν να μετρηθούν στην πραγματικότητα. Συγκεκριμένα, προσομοιώθηκαν τέσσερα σενάρια: τρία που αφορούσαν τρεις διαφορετικές λειτουργίες αυτόνομων οχημάτων και ένα σενάριο χωρίς τη κυκλοφορία αυτόνομων οχημάτων. Τα αποτελέσματα έδειξαν ότι τα αυτόνομα οχήματα προκάλεσαν αύξηση των καθυστερήσεων και των χρόνων διαδρομής του σταθμού λεωφορείων και μείωση της ταχύτητας, δεδομένου ότι διατηρούν χαμηλότερη ταχύτητα από τα συμβατικά οχήματα του σταθμού. Αυτή η προσέγγιση επιτρέπει την αξιολόγηση πιθανών εναλλακτικών λύσεων πριν από την εφαρμογή παρεμβάσεων στην πραγματικότητα, καθοδηγώντας τους ενδιαφερόμενους και τους επαγγελματίες να δώσουν προτεραιότητα σε βασικές πτυχές των μελλοντικών συνθηκών, όπως είναι και η εισαγωγή των αυτόνομων οχημάτων.

Λέξεις-κλειδιά: *Αυτόνομα οχήματα, Μικροσκοπική προσομοίωση, Πραγματικά δεδομένα, Εκτίμηση επιπτώσεων, Σταθμός λεωφορείων.*

1. Introduction

When examining the progress of the automobile industry in recent decades, it becomes evident that there has been a significant advancement in the integration of technologies into new vehicles, regardless of their type (Rajasekhar and Jaswal, 2016). These integrated connected technologies primarily aim to support driving tasks, effectively introducing computerization into vehicles and thereby redefining the role of the driver by altering traditional driving functions (Fagnant and Kockelman, 2015). This computerization has propelled the automobile industry forward, leading to the planning and development of autonomous vehicles (Rajasekhar and Jaswal, 2016). Through computerization, vehicles gain the ability to operate on existing roads and navigate without direct human input (Rajasekhar and Jaswal, 2016). In essence, the ultimate objective of the automobile industry is to create a functional and safe vehicle with the highest level of automation, often referred to as SAE level 5, which represents a fully automated vehicle operating without any human intervention (SAE, 2016). It is predicted that Connected and Autonomous Vehicles (CAVs) will dominate the market share by 2050, provided that the prices of CAVs decrease annually by 15% to 20% (Talebian and Mishra, 2018).

Automated Driving (AD) vehicles have the potential to change the transportation systems radically. More specifically, it is estimated that road safety levels will be enhanced since road accidents will be prevented with AD evolution. Moreover, it is anticipated that the implementation of CAVs will lead to several benefits such as increased road capacity, improved fuel efficiency, and reduced environmental emissions (Elvik, 2021; Fagnant and Kockelman, 2015; Mersky and Samaras, 2016; Ye and Yamamoto, 2018). However, these outcomes are heavily reliant on the proper parametrization of automation systems, as suggested by the studies.

In terms of passenger advantages, a significant portion of the population, including the elderly, children, and individuals with disabilities, will have the opportunity to travel under circumstances that are vastly different from those involving conventional vehicles. Additionally, the prevalence of shared vehicles is expected to rise significantly, as commuters will no longer own their vehicles but instead rely on on-demand services. Furthermore, passengers, and even the designated driver, will be able to engage in non-driving related tasks (NDRTs) during the journey, such as working on electronic devices, eating, drinking, reading, watching entertainment content, and using their phones for texting or calling (Kim et al., 2018).

Simulation approaches have been extensively utilized to investigate the impacts and performance of Autonomous Vehicles (AVs), as evidenced by several studies (Chen et al., 2017; Lam, 2016; Scheltes and de Almeida Correia, 2017; Shen et al., 2018; Talebpour et al., 2017; Zellner et al., 2016). These simulations rely on various data sources, including network geometry, traffic volume, and modal split, to generate inputs. The microscopic simulation employed in these studies enables a detailed estimation of multiple impacts by tracking the interactions of each vehicle with its surroundings and the environment. Furthermore, it serves as a valuable tool for evaluating new traffic control and management technologies, as well as analyzing existing traffic operations (Owen et al., 2000). By modeling traffic flows and considering the traffic characteristics, researchers can simulate the driving behavior of every vehicle within the transportation network, leading to more accurate estimates of emissions (Lopez et al., 2018; Wen-Xing Zhu and Zhang, 2017).

Additionally, the microsimulation method has been utilized in existing literature to analyze traffic conflicts and present a sequence of events along with the contributing factors that lead to these conflicts (Young et al., 2014). A variety of microsimulation studies have been identified conflicts using the Surrogate Safety Assessment Model (SSAM) software to evaluate consequences of different transportation planning (Goh et al., 2014; Preston and Pulugurtha, 2021), control policies (Kronprasert, 2020; Li and Sun, 2019; Ribeiro et al., 2019; Shahdah et al., 2014; Shahdah and Azam, 2021), road configurations (Bahmankhah et al., 2022; Ghanim et al., 2020; Giuffrè et al., 2019; Shahdah and Azam, 2021) as well as transportation innovations (Elawady et al., 2022; Mourtakos et al., 2021; Xin et al., 2019) in terms of traffic safety. Additionally, a recent study by Oikonomou et al. (2023) proposed a methodological framework for estimating crash rates along with network characteristics and traffic measures using a microsimulation conflict-based analysis. According to a study conducted by Papadoulis et al. (2019), the penetration rate of CAVs can potentially reduce traffic conflicts. Furthermore, Teoh and Kidd (2017) estimated that AVs are safer compared to traditional vehicles as they mitigate human error.

The EU SHOW project aims at developing shared automation operating models for worldwide adoption. During the project, real-life urban demonstrations are taking place in 20 cities across Europe in order to investigate the Automated Driving (AD) vehicles integration in public transport, demand-responsive transport (DRT), Mobility a Service (MaaS) and Logistics as a Service (LaaS) schemes. One of the pilot sites of the project is the Madrid mega site, which aims to enable and provide safe, sustainable and integrated people's mobility. Specifically, the site concerns real traffic shuttle service and bus depot operations.

The present study is inspired by the SHOW project and aims to investigate the impacts of real-world AD vehicle operation in a bus depot concerning road safety, traffic and the environment using field data from the Madrid site. For this purpose, the microscopic simulation method was selected using naturalistic data of automated vehicles operations in order to provide impacts that could not be measured in reality. The real-life highly automated vehicles operate in a bus depot placed in the Carabanchel district of Madrid, Spain, which is further designed in the "Aimsun Next" mobility software consisting of 30 nodes and 40 sections. In the simulation model, trajectory data, provided by Tecnalia (TEC) and Empresa Municipal de Transportes (EMT), were considered for three types of automated vehicles: an AD electric mini bus (Gulliver), a 12-meter AD electric bus (Irizar) and an AD electric car (Renault Twizy) that will lead buses from/to charging spots, in a platoon formation, avoiding any disruption of the normal operation into the premises. The prevailing vehicle and pedestrian traffic data provided by TEC and EMT were considered in the simulation model, as well. The simulation scenarios were four in total: three scenarios for each operation of the three AD vehicles (i.e., Gulliver, Irizar and Twizy) and a baseline scenario without the operation of the AD vehicles.

This study is structured as follows; in the next section, the methodology is presented, including the description of the tools that used, specifications of the AD examined vehicles, the simulated network and scenarios as well as the approach of field data integration. Afterwards, the simulation results are presented. Finally, general conclusions are included by presenting a brief description of the aim and results of this study and how stakeholders or policymakers can exploit this study, followed by study limitations and future research proposals.

2. Methodology

2.1 Used tools

In order to provide impacts of the aforementioned AD vehicles operation that are not could not to be measured in reality, the microscopic simulation method was selected. The microscopic simulation conducted in "Aimsun Next" mobility modelling software (Aimsun Next (Version 22), 2019) that is a proprietary software developed and owned by TSS-Transport Simulation Systems. It is a user-friendly interface, which allows users to create and manipulate models easily. The software also includes powerful visualization tools, including 3D models and animations, which help users understand the results of their simulations better. In the software, multiple impacts are able to be exported by modelling realistically traffic flows. Specifically, it is designed to help transportation professionals analyze and optimize the performance of transportation systems, including roads, transit systems, etc. In addition, "Aimsun Next" offers a range of features for transportation planning, including the ability to create detailed models of transportation networks, simulate traffic flow, evaluate different scenarios, and analyze the results. It can be used for a wide range of applications, such as testing new transportation infrastructure. Furthermore, the software utilizes advanced algorithms and models to simulate transportation systems accurately. It can model a range of different transportation modes, including cars, buses, trains, and pedestrians and can also provide traffic, environmental as well as road safety measurements at a high level of detail.

In order to assess safety impacts, the vehicle trajectories were also extracted from the microscopic simulation, and further analyzed using the Surrogate Safety Assessment Model (SSAM) software (Pu and Joshi, 2008). SSAM software is owned by the Federal Highway Administration (FHWA) and is available to download and use from the FHWA website. Specifically, SSAM is a software tool used to evaluate the safety performance of roadway designs and traffic control measures, based on surrogate measures of safety, which are used as proxies for actual crash outcomes. These measures include parameters such as vehicle speed, acceleration, and trajectory, which can be used to predict the likelihood of a crash occurring. By analyzing these surrogate measures, the SSAM software can help identify potential safety issues and evaluate different design options to optimize safety. The software processed the vehicle trajectory data given through the microscopic simulation and identified conflicts. A conflict is identified when the time-to-collision (TTC) and post-encroachment time (PET) are lower from preset thresholds, with 1.5 seconds and 5.0 seconds default values, respectively.

2.2 Automated driving vehicles

The present study aims to investigate the impacts of real-world automated driving vehicle operation in a bus depot concerning road safety, traffic and the environment using field data from real demonstrations in Madrid aiming to enable and provide safe, sustainable and integrated people's mobility. More specifically, these demonstrations taking place in in Carabanchel bus Depot and Empresa Municipal de Transportes (EMT) garage seeking to implement an 'Automated-docking-charging parking' operation. In addition, the demonstrations deploy a fleet of up to five automated driving (AD) passenger vehicles, to complement the existing service offers. The fleet is mixed, composed of shuttles (mini-buses, and a 12 meter-long bus), and of passenger cars (Renault Twizy) for people transport. Moreover, a robot taxi and on-demand service is deployed also based on one Renault Twizy. Therefore, three types of automated vehicles are considered and presented in Figure 1: an AD electric mini bus (Gulliver), a 12-meter AD electric bus (Irizar) and an AD electric car (Renault Twizy) that will lead buses from/to charging spots, in a platoon formation, avoiding any disruption of the normal operation into the premises. All three vehicles are SAE level 4 (SAE, 2016).

***Figure 1:** Real demonstration automated driving vehicles*

Furthermore, the parameters of each vehicle are the following and have been inserted into the simulation as well. Specifically, the Irizar shuttle bus dimensions are 12 m in length and 2.55 m in width and has a total capacity of 60 passengers with 25 passengers seating. Its maximum desired speed is 60 km/h, maximum acceleration 1.36 m/s^2, maximum deceleration 10 m/s^2 and weight 15,845 kg. Similarly, Twizy dimensions are 2.4 m in length and 1.4 m in width. Its maximum desired speed is 80 km/h, maximum acceleration 1.00 m/s^2, maximum deceleration 1.00 m/s^2 and weight 480kg + ~120kg. Additionally, the Gulliver mini-bus has a length of 5.32 m, and a width of 2.116 m. Regarding the maximum desired speed, is 32 km/h and weighs 3.000 kg. Its maximum acceleration is 2 m/s^2, maximum deceleration is 6 m/s^2 and the normal is 4 m/s^2. In addition, it has a total capacity of 25 passengers and 7 who are seated.

2.3 Simulated network

The real-life highly automated vehicles operate in a bus depot placed in the Carabanchel district of Madrid, Spain, which is shown in Figure 2.

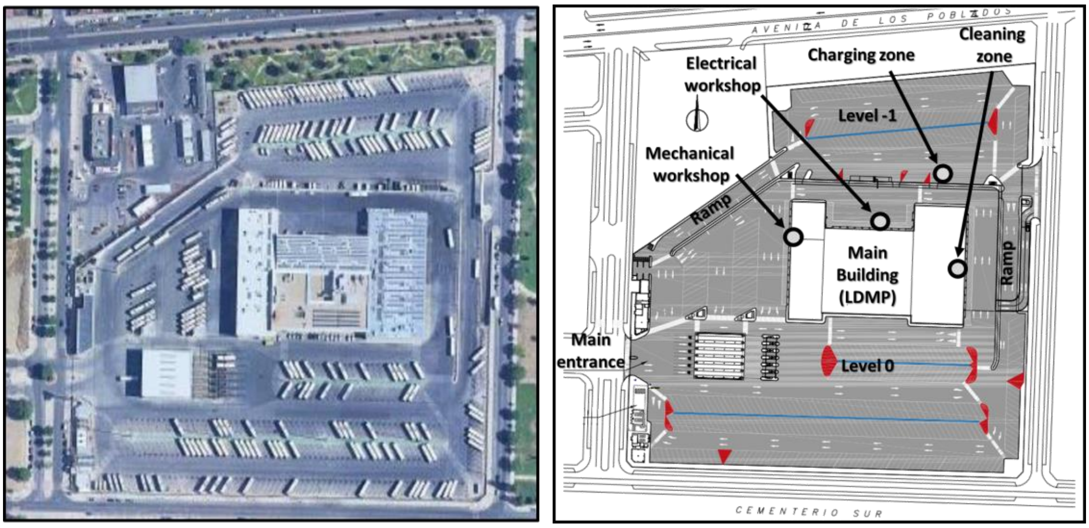


Figure 2: Carabanchel bus depot

The examined bus depot of the Carabanchel site of the city of Madrid, Spain was further designed in the Aimsun Next simulation software. The simulated network, as shown in Figure 3**Error! Reference source not found.**, consists of 30 nodes and 40 sections. The prevailing movements were considered in the model: the vehicle Origin-Destination (O-D) matrices consisted of 11×11 centroids and a total number of 34 cars and 126 buses for a morning hour. The pedestrian O-D matrix consists of 6 entrances and 7 exits and a total number of 211 pedestrians for a morning hour. Parking lots were simulated as centroids since the parking maneuver is not feasible in the simulation software and hence the effect on the network is the same due to the network calibration.

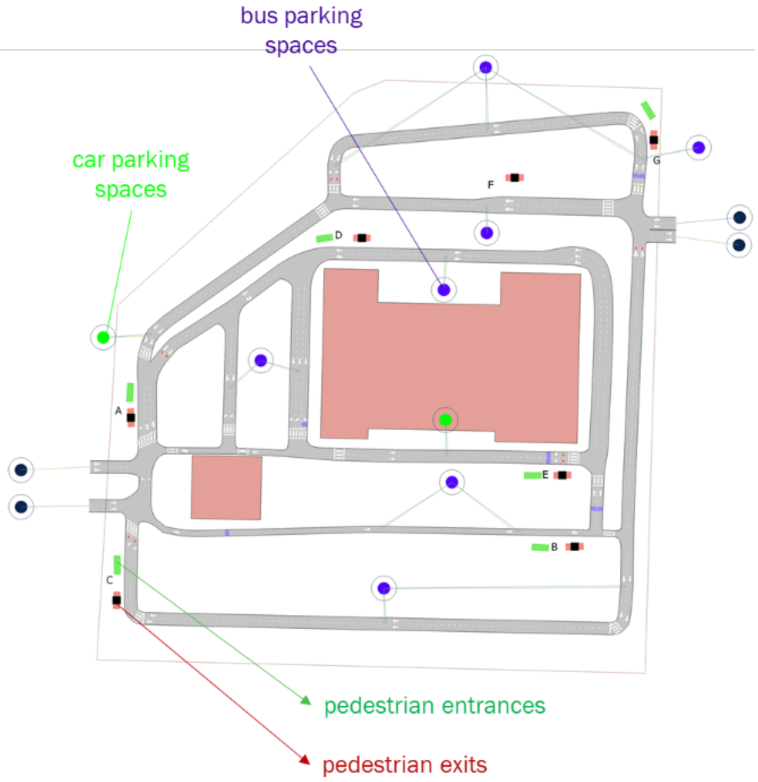


Figure 3: Simulated bus depot network in the simulation software

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. In addition, 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.

2.4 Simulated scenarios

For the Carabanchel bus depot network, four scenarios were considered in the simulations taking into account naturalistic data from the pilot operations of three automated vehicles. Four microsimulation scenarios in total were created: three scenarios for each of the three automated driving vehicles operation (Gulliver, Irizar and Twizy) as well as a baseline scenario consisting of the existing network without the automated vehicle operations. Additionally, 10 distinct replications of each scenario using random seeds (numbers used to initialize a pseudorandom number generator) were also simulated. The simulation time for all scenarios was 1 hour (morning peak hour). For the automation scenarios, only one route/round of each vehicle was completed during the 1-hour slot.

2.5 Field data integration

In the simulation model, trajectory data, provided by Tecnalia (TEC) and EMT, were considered in the simulations for the three types of automated vehicles (Gulliver, Irizar and Twizy) operation with the aim of inserting naturalistic data into the simulation model and several impacts to be extracted. Specifically, the moving buses, cars and pedestrians inside the parking depot within a timeframe were considered during the simulation network development. The real-data were inserted in the simulation in the following way. The AD vehicles route included 19 different sections in the Aimsun model. The main idea was to set a speed limit for each AD vehicle (Gulliver, Irizar and Twizy) for each of the 19 sections according to the provided field data in order to have the most realistic results possible. Based on vehicles trajectories, the real speeds of each vehicle (Gulliver, Irizar and Twizy), as well as the X and Y coordinates, were used in order to estimate the maximum speed for each section (per vehicle). In addition, from trajectory data, the bus stops were found and located in the simulation model as well as the average waiting time, which was 14 seconds. The bus stops as well as the route can be seen in Figure 4**Error! Reference source not found.**. Nevertheless, Twizy which is a light-weighted passenger vehicle drives the entire round without stops.

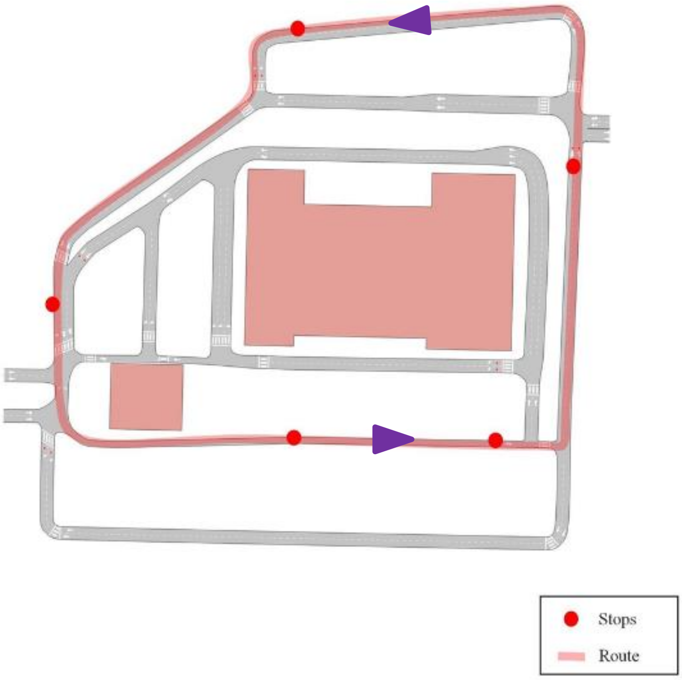


***Figure 4:** Automated vehicles circular routes and stops*

2.6 *Extracted KPIs*

The simulations were carried out in Aimsun Next software, which exports data that will enable to evaluate several Key Performance Indicators (KPIs). These KPIs can be classified into groups including "Road safety", "Traffic efficiency," and "Environment and energy efficiency". Multiple metrics assessing the impacts of AD vehicles in different traffic conditions were derived through the microscopic simulation. It should be mentioned that many additional and detailed measurements can be extracted using the microsimulation model but only the most important are reported here. The definition of the plotted measurements along with the corresponding related KPI follow:

Road Safety

- Conflicts: the number of conflicts with other road users and infrastructure during the AD operation (count)

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

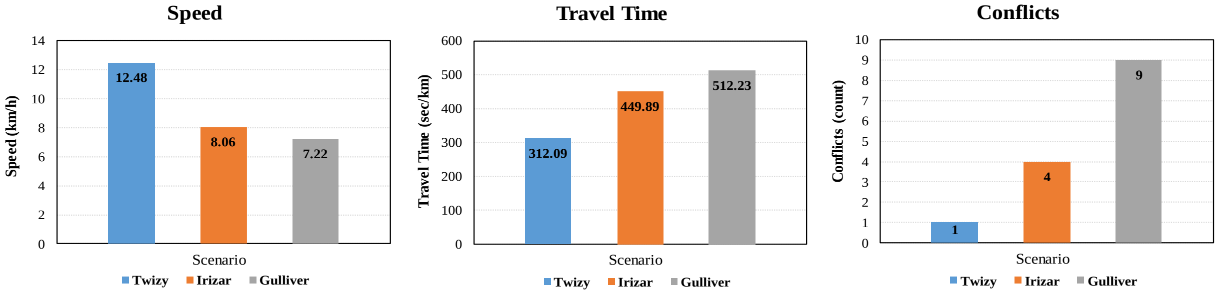
- CO_2 Emissions: total carbon dioxide emissions (g)
- NO_x Emissions: total nitrogen oxides emissions (g)
- PM Emissions: total particulate matter emissions (g)

3. Results

The results of the bus depot simulations were grouped in three groups of plots i.e. Vehicle Level, Network Level and Pedestrian Level, as shown in Figure 5.

(a)

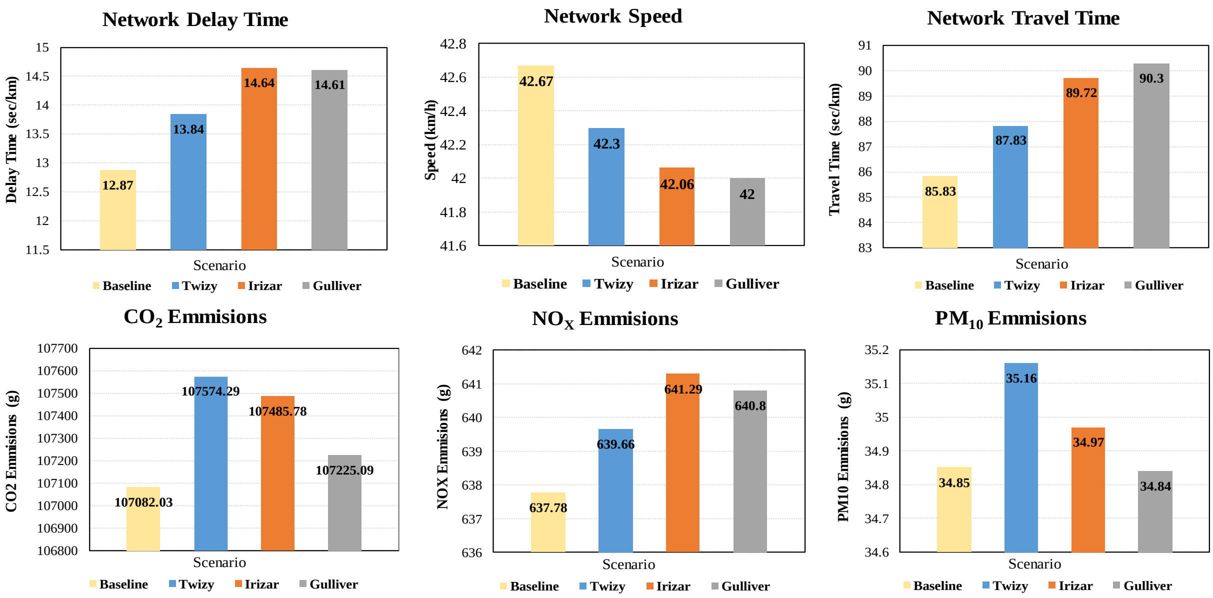
Vehicle Level:



Speed · Travel Time · Conflicts

(b)

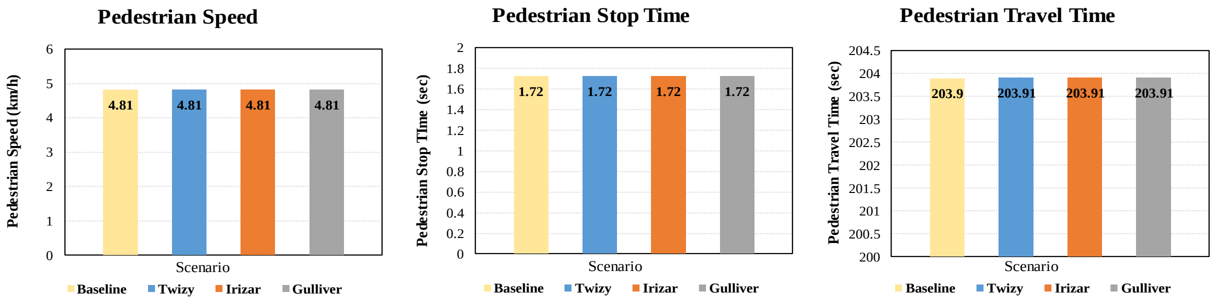
Network Level:



Network Delay Time · Network Speed · Network Travel Time · CO_2 Emmisions · NO_X Emmisions · PM_{10} Emmisions

(c)

Pedestrian Level:



Pedestrian Speed · Pedestrian Stop Time · Pedestrian Travel Time

Figure 5: *Impacts of AD vehicles operations in Carabanchel bus depot: on (a) vehicle level, (b) network level and (c) pedestrian level*

Considering the extracted values from the microsimulation (Figure 5), Twizy seems to have a higher speed throughout the entire route since it is a light-weighted passenger vehicle compared to the others, which are characterized as buses. The speed trend is also reflected to travel time, meaning that with lower speeds, higher travel times are recorded. Additionally, conflicts, that the AD vehicles were involved in, seem to have the exact opposite trend compared to speed. Probably due to the fact that a vehicle operating with a higher speed results a shorter trip duration with lower interactions with other vehicles inside the bus depot. Concerning the network level and more specifically the traffic impacts, all three vehicles seem to increase network delay time and travel time as well as decrease network speeds since all AD vehicles are slower than the manually driven vehicles that coexist in the network. The trends of the aforementioned measurements follow the opposite trend of speed, as it is rational. Focusing on the environmental impacts, all three vehicles seem to increase environmental emissions more than the current baseline conditions. However, the following trend needs further research to understand the different patterns observed within the vehicles and emissions. Finally, on pedestrian level, pedestrians' speed, stop time and travel time seems to remain unaffected by the operations of the different vehicles, probably due to the fact that there were several crossings in the depot.

4. Conclusions

The present study aims to support a real AD vehicle implementation conducted in a bus depot in Madrid, Spain within the EU SHOW project. The microscopic simulation methodology was applied in order to investigate impacts of AD vehicles operation that could not be measured easily in reality. More specifically, four different scenarios were tested: three scenarios involving three different AD vehicle operations and a baseline scenario without AD traffic. The results indicated that the operation of automated driving vehicles increases bus depot delay time and travel time, while decreases average speed due to the fact that autonomous vehicles tend to operate at reduced speeds in comparison to manually driven vehicles that coexist in the bus depot.

To that end, traffic simulation, as a solid approach, enabled testing of new mobility technologies and examining the impacts of alternatives before real-life interventions such as the present case studies including the introduction of automated driving services. Moreover, traffic simulation approach gave the ability to model and analyze complex traffic scenarios, such the investigation of AD vehicles operation on traffic flow and safety. The followed methodology allowed to simulate scenarios including field trials driving data of automated driving vehicles and examine their interactions with human-driven vehicles as well as with pedestrians. The obtained results could guide stakeholders and practitioners as the examined scenarios included fundamental aspects for future conditions, such as automated driving vehicle operations. Findings can also help accelerate the development and deployment of autonomous vehicles and improve their safety and reliability on the roads. From the knowledge gained from the microsimulation, insights could be derived for critical factors that should be taken into account for the development of sustainable urban mobility.

On the contrary, the present research does have certain limitations. Since traffic microsimulation was employed, assumptions regarding automated driving modelling were unavoidable. Impacts of specific automated driving operations were investigated while specific KPIs were obtained from simulations. Additional KPIs, except for the examined ones, will be able to shed light on further impacts of automated driving services operation on traffic, safety and the environment that were not investigated. Experiments investigating additional AD operations and services could further enrich the impact assessment of automated transport systems.

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