Evaluating Traffic Control Strategies for Autonomous Shuttle in Different AV Penetration, Using SUMO Traffic Simulation

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Abstract. The rapid growth of autonomous vehicles (AVs) and traffic strategies promises to transform urban mobility, necessitating a comprehensive investigation of their impacts on traffic. This study assessed the effects of different traffic control strategies on a network with an autonomous vehicles shuttle and varying levels of AV penetration. The simulation of Urban Mobility (SUMO) software was utilized as an open-source and flexible traffic microsimulation, creating a realistic simulation environment. Three traffic control strategies for shuttle movements were examined in a section of Turin, Italy: mixed traffic, dynamic lane, and separated lane strategies within the network. Each strategy was evaluated across five AV penetration levels.

The simulation results demonstrated that increasing the AV integration leads to reduced travel times and greater road efficiency. Both the separated lane and dynamic lane strategies improve travel times for the shuttle but have negative effects on other vehicles. However, the dynamic lane offers improvement for the shuttle while causing a lower negative impact on other vehicles compared to the separated lane strategy. Dynamic lanes offer a flexible and effective solution for modern traffic management, helping cities improve their mobility and reduce congestion. The findings highlight the importance of developing various control strategies and AV-compatible infrastructure to achieve traffic efficiency, reduced congestion, and an updated urban mobility framework.

Keywords: Traffic Control Strategy · Dynamic Lane · Autonomous Shuttle · Autonomous Vehicles (AVs) · Traffic Microsimulation · SUMO

1 Introduction

The research and development of traffic control strategies and AVs have seen rapid advancements in recent years, and simulations play a pivotal role in advancing development. Researchers and engineers rely on sophisticated simulation environments to model and evaluate the performance of autonomous systems in diverse and controlled scenarios. Simulations offer a safe and cost-effective means of testing and validating

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autonomous algorithms and control systems prior to real-world deployment [1]. Traffic simulation frameworks provide a helpful tool for answering complex research questions and evaluating traffic management strategies and their impact.

Many studies on the impact of AVs on Traffic parameters have focused on microscopic simulation. The detailed simulation of microscopic models is more precise, particularly when emissions or individual routes are simulated [2]. They can simulate a wide range of scenarios, from regular daily traffic patterns to uncommon events, such as accidents or road closures. Among microscopic traffic simulators, SUMO (Simulation of Urban Mobility) is a free and open-source package designed to handle large networks. SUMO enables the simulation of individual vehicles within road networks, thereby providing a platform for exploring a wide range of traffic-management topics.

While SUMO can run independently, complex traffic simulations with interactive control rely on the Traffic Control Interface (TraCI) library. TraCI serves as a bridge between Python and SUMO, enabling the definition of simulation scenarios, as well as control and dynamic interaction with the simulation through Python scripts.

This study aims to simulate the interactions between future autonomous shuttles autonomous vehicles, and human-driven vehicles under various traffic control strategies using SUMO, and to assess their impact to contribute to a deeper understanding of control strategies, AVs, and their roles in future urban mobility systems.

2 Related Works

In the context of impact of AVs on traffic flow, Nippold et al. studied the traffic flow and maximum capacity of signal-controlled intersections in Düsseldorf by using the SUMO traffic simulation tool in the presence of AVs. The results, integrated into the MATSim simulation, showed that AVs might decrease the maximum traffic capacity with a nearly linear reduction in capacity as AV penetration increases. Specifically, the maximum traffic flow rate decreased by more than 10% when comparing 100% conventional vehicles with 100% AVs [3].

In a study conducted by Lu, the impact of different penetration AVs on traffic parameters was investigated. The AVs were simulated in the SUMO traffic simulation suite with different driving parameters compared to conventional vehicles. Six scenarios with different AVs penetrations (from 0 to 100%) were simulated for grid and real-world networks. The results show that the capacity increases quasi-linearly with higher AVs penetration for both networks. In the grid network, the maximum flow increased by 16.01%, considering the 100% AVs penetration scenario with only conventional vehicles. For the real-world network simulation, the increase of maximum flow is around 25% from the 0% AVs penetration to purely AVs scenario [4].

Park et al. studied the impact of AVs on urban traffic flow and road capacity using a real-world network case study and VISSIM microsimulation. It simulates scenarios with varying AV penetration rates and traffic volume. The findings reveal that AVs significantly enhance traffic flow by reducing travel time and delay and increasing vehicle speed, especially at 100% penetration, with 17% time savings, 31% delay reduction, and 21% speed improvement. This study highlights the potential risk that if AVs increase overall car use, they can strain traffic management. Conversely, with all vehicles as

AVs, the current road network can handle 40% more traffic without additional road construction [5].

The dynamic control strategy is an advanced method of traffic management that adapts to real-time traffic conditions to optimize the flow of vehicles. This system often uses a combination of inductive loop detectors, infrared sensors, and cameras to detect vehicles. Advanced systems can be integrated with connected vehicle technologies, where vehicles communicate directly with the infrastructure, providing another data source for traffic management [6]. It reduced congestion, improved traffic flow, lowered emissions owing to reduced delays at intersections, and enhanced safety.

In another study, authors use Vissim, to compare the effectiveness of different bus lane management strategies at four selected locations in Rzeszów, Poland. These sites were chosen due to their similar length and traffic characteristics. The study evaluated three different options: no bus lanes, traditional exclusive bus lanes, and dynamic bus lanes. The dynamic bus lanes system was designed to activate only when buses were detected, allowing other vehicles to use the lane at other times, thereby optimizing lane usage. Results showed that dynamic bus lanes provided comparable benefits to buses as exclusive bus lanes but caused a much smaller increase in travel times for private vehicles. For instance, XBLs increased travel times for private vehicles by 12% to 25%, while DBLs only increased it by 1% to 12% [7].

Othman and Shalaby evaluated the effectiveness of Dynamic Bus Lanes compared to Exclusive Bus Lanes and mixed traffic operations under varying traffic demands and transit frequencies using AIMSUN simulations in Toronto, Canada. The results revealed that Dynamic Bus Lanes have the potential to improve the overall corridor performance over a wide range of traffic and transit service conditions, particularly under intermediate traffic demand levels. On the other hand, Exclusive Bus Lanes can be an efficient prioritization strategy that improves overall corridor performance under high traffic demand. Li et al. [8].

Optimized dynamic lane reservation for public transport, focusing on minimizing the impact on regular vehicles, while maximizing traffic efficiency for dynamic lane users. This approach utilizes bi-objective optimization and an improved evolutionary algorithm, featuring a hybrid crossover strategy for robustness and effectiveness. The proposed method was tested on a large-scale network. Their results showed that the dynamic lane approach is more effective for urban traffic efficiency than the previous models [9].

Scientific literature has investigated the potential impacts of AVs and traffic control strategies, such as dynamic lanes, on improving traffic capacity, and efficiency within existing mobility systems. Most research on AVs has focused on highway improvements, whereas only a few studies have addressed their impacts on urban transportation. Furthermore, the impacts of AVs and various traffic control strategies have not been fully explored.

3 Case Study

In the framework of the H2020 SHOW European project, [10] two automated shuttles were tested in real traffic in the Municipality of Turin (Italy) for future public transport. The shuttle can operate on both public and private roads with a high-performance guidance and detection system to adapt its navigation system to various situations. The shuttle can transport up to 15 passengers [9].

A fleet of automated shuttles can run along public roads, offering an on-demand transport service. Owing to the limited speed of the shuttles along the authorized route (speed limit is set to a maximum value of 18 km/h for safety reasons), congestion and slowdowns may occur when the shuttle are operating.

In this study, the shuttle path and outputs from the SHOW project were used as input data for the simulation. The simulation area was located at the center of Turin, which is the same area as the SHOW project. It covers the section bordered to the south by Corso Maroncelli, between the intersections of Via Ventimiglia and Via Genova, and to the north by Corso Spezia (Fig. 1). The shuttle is simulated along this route with 7 stop stations, where it stops for 30 s at each one. Ventimiglia has two lanes in each direction, from Corso Maroncelli to Corso Caduti sul Lavoro, while the rest of the street has only one lane. Therefore, a part of this section was selected to implement the traffic scenarios. Traffic control strategies were implemented on Via Ventimiglia, between Via Valenza and Corso Maroncelli, which includes two shuttle stop stations.

Fig. 1. Simulation area in Torino

The simulation was conducted using three distinct traffic-control strategies. These scenarios were defined and implemented using TraCI in SUMO.

In the first traffic control strategy, mixed traffic control was used for shuttles, AVs, and human-driven cars. This approach avoids prioritization or restrictions on any vehicle type. All vehicle categories shared road spaces, without any type receiving preferential treatment. In a mixed traffic environment, all vehicles interact with each other, which can create challenges for managing safety, predictability, and efficient traffic flow. This strategy was selected as the base scenario and served as a benchmark for comparing the effectiveness of the subsequent strategies.

The second traffic control strategy is a separate lane for shuttles in Via Ventimiglia, from Via Valenza to Corso Maronceli. A separated lane strategy involves creating lanes that are physically or visually separated from general traffic, and reserved for particular types of vehicles or purposes, such as bicycles or public transit. The consequence of this lane allocation is a reduction in lane availability for the other types of vehicles. The primary goal is to prioritize shuttle within the traffic network.

The third traffic control strategy involves the implementation of a dynamic lane system. A dynamic lane strategy refers to a flexible road lane management system in which lanes are reassigned dynamically based on priorities to serve specific vehicle types or purposes. Such as bicycles, or public transit vehicles. This was applied to sections of the network along Via Ventimiglia, from Via Valenza to Corso Maroncelli. This strategy aims to provide protection and prioritization for the shuttle, enhance user interest, and ensure smooth operation.

These scenarios were implemented using five different penetration levels of AVs and the defined AVs. In addition, 0%, 25%, 50%, 75%, and 100% penetration of the AVs.

4 Methodology

4.1 Traffic Behavior Models

Behavioral models in traffic simulations, such as lane-changing and car-following models, are essential components that define how vehicles interact with each other and navigate road networks. These models aim to replicate real-world driving behaviors, thereby enabling realistic and accurate traffic simulations.

Car-following models are mathematical representations used in traffic flow theory and simulations to describe how individual vehicles adjust their speed and spacing relative to other vehicles on a road. The Intelligent Driver Model is a car-following model designed to capture the behaviours of real-world drivers by considering factors such as the desired speed, minimum gap, time headway, and comfortable deceleration. It offers a realistic representation of how drivers adjust their speeds in response to traffic conditions [12]. IDM can be used to model a wide range of traffic conditions, from free-flowing traffic to congested scenarios. Its parameters can be adjusted to simulate various driving behaviours [13]. In this simulation, the IDM Car-following model was implemented for the vehicles.

Lane changing, as another model in traffic simulation behavior, is a crucial aspect of traffic flow and microscopic traffic simulations. These models aim to capture the complexity of the lane-changing dynamics and enhance the realism of traffic simulations. However, for AVs, lane-changing models are evolving owing to fundamental differences in decision-making between humans and machines. AVs rely on sensor data, environmental predictions, and safe execution, thereby introducing greater complexity. SUMO supports customizable vehicle behavior, enabling the implementation of various lane-changing models. In this article we use the LC2013 model, that incorporates psychological aspects such as impatience, making it a realistic model in simulating AVs and human-driven vehicle in lane-changing behavior.

4.2 Simulation Networks

The generation of road networks for SUMO can be accomplished in several ways, including manual creation, using Open Street Map (OSM), or importing maps from other simulation software, depending on the complexity of the network and the available data sources [14]. Complex Road networks often involve a combination of methods, owing to the differences between the input map details and real details. In this simulation, a combination of methods is used to create a more realistic network. The map imported by the "OSM Web Wizard" from the OSM was based on the road network. (Fig. 2) Due to differences between OSM and reality in details like the number of lanes, traffic signal cycles, shuttle stops, and speed limits, the imported map is reviewed and modified manually.

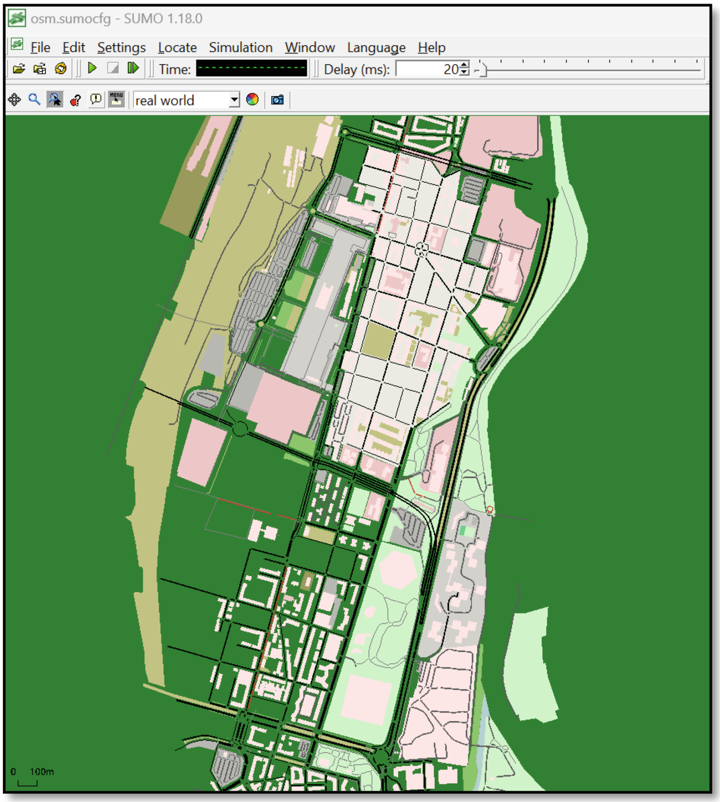

Fig. 2. Simulation Area in SUMO

4.3 Simulation Parameters

Humans primarily rely on visual cues, which can be subjective and sometimes influenced by cognitive biases or distractions. However, AVs use an array of sensors (LiDAR, radar, cameras, ultrasonic sensors, etc.) that provide objective and quantified data regarding their surroundings. This dataset is processed rapidly for decision-making. This affects the Reaction Times and AVs can react almost instantaneously. These differences change the parameters of the simulation models of AVs compared to those of human-driven vehicles. In the SUMO simulation, vehicle parameters are defined for each vehicle type and are pivotal for generating accurate and realistic traffic simulations. This definition represents different vehicles such as cars, trucks, and buses. The key attributes of these types include vehicle dimensions, speed limits, acceleration and deceleration rates, lane-changing behavior, fuel consumption, emissions, and preferred routes. SUMO offers customization to simulate the distinct behaviors of various vehicles ranging from passenger cars to autonomous vehicles. In this simulation, the SUMO parameters were modified based on Table 1 to define AVs and other vehicle types.

Table 1. Parameters of the driver model used in SUMO simulations [4]

Type Car	Min Gap (m)	Accel (m/s^2)	Decel (m/s^2)	Emergency decel (m/s^2)	Max Speed (km/h)
Human Driver	1.5	3.5	4.5	8	50
AVs	0.5	3.8	4.5	8	50
Shuttle	0.5	0.8	1.5	3	18

- Mingap: the offset to the leading vehicle when standing in a jam
- Accel: the acceleration ability of vehicles
- Decel: the deceleration ability of vehicles
- Emergency Decel: the maximum deceleration ability of vehicles

SUMO offers flexibility in customizing traffic flow types to represent various vehicle categories and their unique characteristics. This customization allows for the modeling of a wide range of scenarios and defines public transportation, emergency services, and freight transport. SUMO's flexibility in managing various traffic definition methods makes it a powerful tool for simulation. Traffic flows in SUMO can be defined and generated using several methods including direct flow definition, origin–destination (OD) matrices, turning percentages, random routes, flow distribution over time, public transport flows, and importing real-world data. These methods were chosen based on data availability. Combining or refining methods leads to more realistic and complex traffic simulations in SUMO.In this study, input traffic data were gathered through manual traffic counts at key intersections, while other network flows were assumed. Based on this, around 10,000 vehicles per hour inserted into the simulation network. Vehicle routes were generated using "jtrrouter," a Python script designed to randomly distribute traffic throughout the network. The selected route for the shuttle is defined in the routes file, which includes stops and their stop times.

The traffic scenarios in this study were designed and managed using TraCI in the SUMO environment. TraCI plays a central role in continuously monitoring and controlling the simulation by interfacing with Python scripts. This real-time interaction enables dynamic adjustments to traffic configurations based on simulated events.

To implement a dynamic lane in SUMO (Fig. 3), a specific point within the network is defined using TraCI. As the shuttle approached a predefined section, TraCI detected its presence and activated a dynamic lane in the upcoming segment until the next intersection. This dynamic lane assignment designated the first lane exclusively for shuttles, temporarily restricting access to other vehicle types. Once the shuttle traverses the dynamic lane section, allowing TraCI to revert the status of the first lane, the restricted lane becomes accessible to all vehicles, thereby restoring the standard traffic flow.

To implement the separated lane strategy, the properties of the lanes were modified using NetEdit, a graphical network editor within the SUMO. These modifications were made to restrict access to selected lanes and allow shuttles to operate in these lanes.

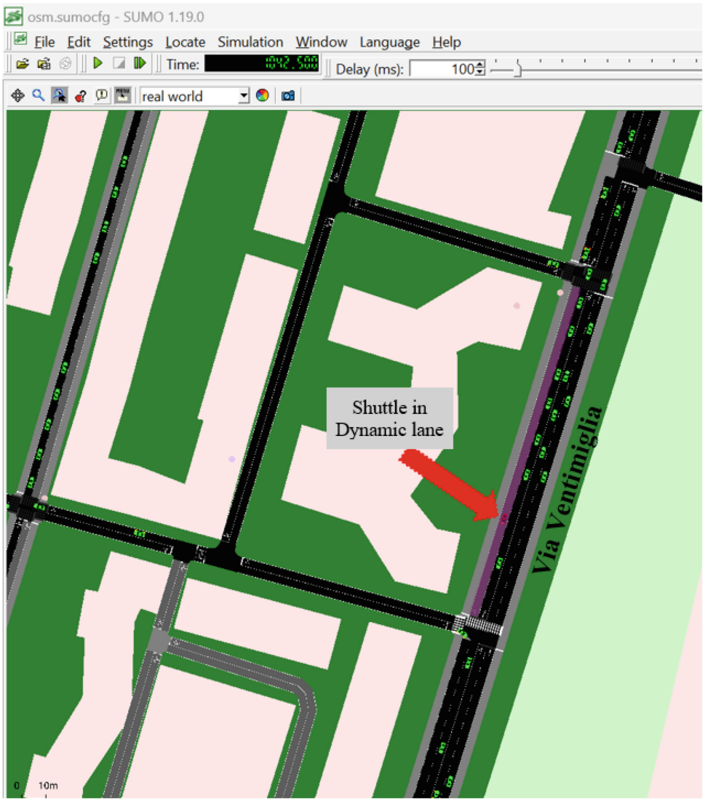

Fig. 3. Simulation of Dynamic Lane in SUMO

5 Simulation Results

Each scenario was simulated 10 times with different random seeds to account for variability in trip and route generation as well as simulation dynamics. The traffic efficiency of the vehicles was observed using the travel time in test sections of traffic strategies. The parameters were disaggregated by vehicle type to determine whether control strategies had a positive effect. The simulations were performed for a duration of 1 h. The results are aggregated and presented in Fig. 4 and Fig. 5 for various traffic strategies under different AVs percentages.

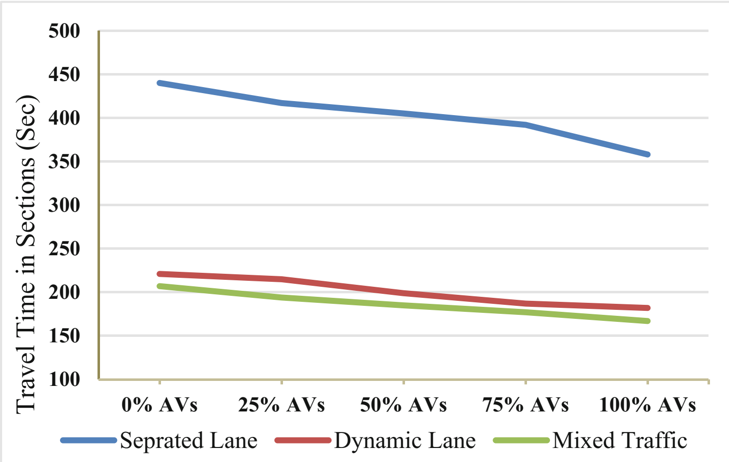

Fig.4. Travel time of vehicles in different strategies and AVs percentages in selected sections

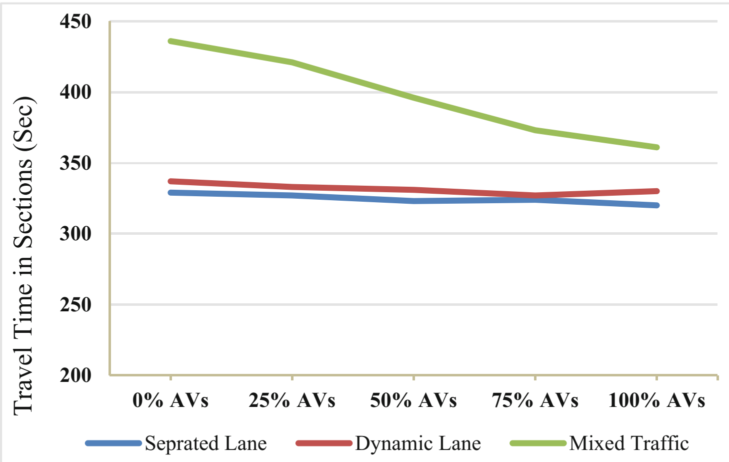

Fig. 5. Travel times of the shuttle in different strategies and AVs percentages in selected sections

In the Mixed Traffic Strategy, the travel time for both vehicles and shuttles decreased as the percentage of AVs increased. Vehicles showed a steady improvement, with decreasing 19.3% in travel times, from 207 s at 0% AVs to 167 s at 100% AVs. Similarly, Shuttle travel times start at 436 s in a fully human-driven scenario and progressively decrease to 361 s in a fully AV-based environment, it is around 17.6% reduction in travel time.

These results indicate that integrating AVs into a mixed traffic environment has a substantial positive effect on overall network performance. In mixed traffic, AVs can react faster to changes, maintain smoother acceleration and deceleration patterns, and effectively optimize space, all of which lead to reduced overall travel times. This behaviour not only improves the efficiency of general traffic but also enhances the reliability and punctuality of shuttle services, which is crucial in an urban setting where public transport plays a vital role in reducing congestion.

In the Dynamic Lane Strategy, vehicles also experienced decreasing 17.6% travel times by increasing AVs penetration to 100%. However, overall travel times increased by approximately 11.7% on average compared to the Mixed Traffic Strategy. For shuttle, travel times decreased by an average of 16.5% compared to the Mixed Traffic Strategy but remained approximately constant despite changes in the percentage of AVs.

The dynamic lane strategy benefits from its inherent flexibility, allowing lane allocation to change based on real-time traffic needs. The adaptability of dynamic lanes allows urban planners to adjust traffic flow patterns dynamically, which can be useful during peak hours or special events where shuttle reliability and consistency are key. The fact that shuttle travel times remained stable regardless of AV penetration highlights the robustness of dynamic lane strategies in supporting public transit without significantly disadvantaging other vehicles. This adaptability demonstrates a strong advantage of dynamic lane management, especially in the context of cities aiming to prioritize public transport while managing private vehicle congestion.

Similar patterns were observed for the Separated Lane Strategy. Travel time of vehicles improved 20.2% by changing penetration of AVs from 0% to 100% AVs. In comparison with the Mixed Traffic Strategy, there was an average increase of 126.7%. For shuttles, travel times decreased by the average of 18.2% compared to the Mixed Traffic Strategy but low reduction regardless of the proportion of AVs.

The results suggest that the implementation of separated lanes has both benefits and challenges. The advantage lies in its ability to provide a dedicated lane for shuttles, effectively eliminating interference from other vehicles, thus ensuring consistent and predictable travel times. However, this dedication of lanes also results in reduced road capacity for general traffic, leading to increased congestion in the remaining lanes. The increased travel time for regular vehicles implies that separated lanes may not always be the best strategy, especially when road space is limited, and it is essential to manage the flow of both public and private vehicles equitably.

A key insight from the simulations is that increasing AV penetration has a positive effect on overall network performance across strategies. The benefits were most notable in the Separated Lane Strategy, where the introduction of AVs led to a more reduction in travel time. The ability of AVs to travel more closely together and make quicker adjustments helps mitigate the bottlenecks created by the reduced road capacity associated with separated lanes.

The shuttle also benefits from the introduction of AVs. This improvement is the highest, by 17.2%, in the mixed traffic by changing AVs from totally human driven to fully automated vehicles.

The findings of this study highlight the influence of traffic control strategies on the effectiveness of urban networks. Among the strategies analysed, separated lanes offer substantial benefits for shuttle travel times but result in increased travel times for other vehicles. In contrast, dynamic lane strategies improve shuttle travel times with only a slight impact on general vehicle traffic. This makes dynamic lanes an attractive option for cities looking to optimize road usage while maintaining flexibility.

Dynamic lane strategies demonstrate advantages in their ability to respond adaptively to real-time traffic conditions. By prioritizing public transportation and optimizing the available road capacity, dynamic lanes offer a modern solution to urban traffic management. The flexibility in dynamic lanes allows for more efficient allocation of road space, improving the efficiency of public transit without unnecessarily affecting the travel times for other vehicles. As cities increasingly move towards smart and connected infrastructure, the use of dynamic lane strategies becomes even more relevant, providing adaptable solution that aligns with the goals of modern urban mobility.

6 Conclusions

AVs represent a frontier for innovation in urban mobility and promise transformational changes in urban traffic. This study focuses on evaluating various traffic control strategies under different AV penetration levels using the SUMO microsimulator. Across all strategies, as the AV percentage increased, there was a decrease in the travel time for vehicles. The greatest improvements for vehicles were observed with the implementation of separated lanes, where the implementation of the strategy led to an increase in the flow within remain lanes. This outcome demonstrates the significant impact of AVs under higher traffic congestion conditions that is due to their characteristic behaviours and reaction.

The results show that traffic control strategies have a significant impact on the effectiveness of urban networks. When comparing different strategies, separated lanes significantly improved the travel times for the shuttle but notably increased it for other vehicles. However, dynamic lane strategies improved the travel times for the shuttle compared with mixed traffic, with only a slight increase in travel times for both AVs and human-driven vehicles.

Dynamic lane strategies offer benefits by adapting to real-time traffic conditions, optimizing road usage, and providing adaptable solutions to traffic-management challenges. Changes in the traffic levels can impact the effectiveness of these strategies, due to delays at intersections.

This work also demonstrates the capabilities and flexibility of SUMO, as a free and open-source software, in implementing and simulating traffic scenarios. Although simulation studies provide useful insights, real-world testing is required to validate these results. Closing the gap between the simulation and real-world performance is crucial to ensure that the predictions are accurate and applicable in practical situations.

7 Future Work

In our upcoming projects, it will be pivotal to use real-time human-driven data sourced from AVs. The real-time data provided, stemming from connected vehicles and their continuous interaction with other vehicles, infrastructure, and even pedestrians, offer a more dynamic approach to simulating and managing urban traffic scenarios. The SUMO can be calibrated and validated using real-time data streams. The simulation outputs were continuously compared with the real-time data. This ensured that the simulation accurately reflected the current traffic scenario.

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