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Simulation Modelling Practice and Theory

Transitioning to a driverless city: Evaluating a hybrid system for autonomous and non-autonomous vehicles☆

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A R T I C L E I N F O

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A B S T R A C T

Autonomous vehicles will transform urban mobility. However, before being fully implemented, autonomous vehicles will navigate cities in mixed-traffic roads, negotiating traffic with human-driven vehicles. In this work, we simulate a system of autonomous vehicles co-existing with human-driven vehicles, analyzing the consequences of system design choices. The system consists of a network of arterial roads with exclusive lanes for autonomous vehicles where they can travel in platoons. This paper presents the evaluation of this system in realistic scenarios evaluating the impacts of the system on travel time using mesoscopic traffic simulation. We used real data from the metropolis of São Paulo to create the simulation scenarios. The results show that the proposed system would bring reductions to the average travel time of the city commuters and other benefits such as the reduction of the space required to handle all the traffic.

1. Introduction

Autonomous Vehicles (AVs) can have a significant impact on urban mobility and city design [1], such as increasing vehicles safety [2], decreasing cities' congestion [3], and required space for parking [4]. New forms of mobility services, such as shared mobility and carpooling, are changing mobility behaviors and opening the path for full autonomy. However, a simple replacement of Human-driven Vehicles (HVs) with autonomous cars will not solve the traffic problems. If the prospects of full autonomy might bring important benefits to current traffic problems, the transition phase will see a period of autonomous vehicles negotiating traffic with human-driven vehicles. This period of co-existence will, most likely, last for several years.

With the recent emergence of ride-sharing systems such as Uber and Lyft, users in certain cities are substituting collective and active modes of transportation, such as buses and subway, with ride-hailing cars [5]. This can have a negative impact on the public transportation system as well as more traffic, pollution, and environmental impact [6]. A future with highly-effective autonomous vehicles (AVs) may increase private transportation prevalence with all these negative impacts. Adopting a model in which AVs are smaller than regular cars and are capable of forming platoons is a compromise solution that we investigate here.

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This paper addresses this transition phase, simulating a system of AVs co-existing with human-driven vehicles. Since AVs can exchange data with each other and with the urban infrastructure, it is possible to define control algorithms to synchronize vehicles. For example, cars with similar routes can form platoons, increasing road capacity and fuel efficiency, and benefiting from traffic signal green waves [7].

To provide insights into the potential benefits of platooning in an urban environment, in this paper, we systematically analyze a transition from human-driven to autonomous vehicles in which both co-exist in the city streets. This transition follows four phases: (1) exclusive lanes for autonomous cars, (2) the formation of platoons, (3) the design of long bidirectional green waves for the existing traffic signals, and (4) the synchronization of the platoons with the road traffic signals. We ran our model using InterSCSimulator, an open-source, scalable simulator for large-scale smart city scenarios.

To evaluate the AV platoons' impacts, we simulated this proposal in one of the main arterial roads in the metropolis of São Paulo, Brazil, Paulista Avenue. We evaluated multiple incremental scenarios to assess each proposed change's impact from the current situation to full deployment. First, we simulate (i) the current configuration of the Avenue based on real data measured in the city; then, we simulate (ii) exclusive lanes for autonomous vehicles, (iii) smaller autonomous vehicles (40% smaller than the regular cars, called here AV pods), (iv) AV pods platoons, and, finally, (v) the synchronization with the traffic signals. Each of these simulations adds a new improvement over the previous one to evaluate the impact of each change in vehicle dynamics.

The most important contribution of this paper is to provide quantitative evidence for the impact of AV platoons in improving the traffic flow in a real, large-scale urban scenario. Previous research around AV platoon simulation considers either small scenarios or synthetic data. Important findings of our research include:

- Simply replacing human-driven cars by AVs produces a limited impact on city traffic. The reduction in travel time is modest with around 1/3 of the cars being replaced by AVs.
- The formation of AV pod platoons can have a considerable impact on the city traffic, decreasing travel time very significantly.
- When the number of AVs in the system grows to include all vehicles, only one of the four lanes of Paulista Avenue would be enough to handle all the current traffic, releasing a large portion of extremely valuable land back to the city, which can then use it for more interesting uses such as leisure and green areas.

The remainder of this paper is organized as follows. In Section 2, we discuss Autonomous Vehicles, define the AV system, and describe InterSCSimulator. Section 3 presents related work on the simulation of autonomous vehicles. In Section 4, we describe all the simulated scenarios. Section 5 presents the traffic signal timing plan. Section 6 presents the simulation results. In Section 7, we present our major findings and discuss its limitations. Section 8 presents our conclusions and indicates possible future works.

2. Background

Before analyzing the impact of a hybrid system enabling the sharing of roads between autonomous and human-driven vehicles, we discuss the transition to AVs, introduce the proposed AV system, and describe the simulator we used.

2.1. Transitioning to autonomous vehicles

Despite all media, research, and industry excitement, the road to full autonomy is bumpy. Autonomous vehicles might decrease traffic casualties by more than 90% [8,9] and dramatically reduce parking demand in cities [10]. However, the full consequences of their wide adoption on urban form and interaction with other urban infrastructures are still unclear [11,12]. What is clear is that from degree zero of autonomy, when drivers have full control of the car, to degree five, when vehicles are fully autonomous and can operate in any driving scenario without the intervention of humans at any point, there will be a phase of mixed traffic, when human-driven and autonomous vehicles will share the road and negotiate traffic. In fact, vehicles with some degrees of autonomy are already common; for instance, when steering or accelerating can be performed automatically (degree one), or when some functions respond based on information about the driving environment (degree two), although the driver must be ready to take over the wheel.

In most of the current pilot projects, the transition between human-driven and autonomous vehicles is happening in regular mixed-traffic roads. However, instead of exclusively building autonomy within vehicles, we could consider a distributed intelligence [1], in which the road infrastructure (streets, traffic lights, streetlights, curbs) will contain digital technologies gathering and exchanging data. In this way, the city would assist the autonomous vehicles decisions such as the best route to take and which speed to adopt.

With AVs, it will be possible to develop multiple control algorithms to improve city traffic. Vehicles will have high processing capacity and will be able to communicate with the city infrastructure and other vehicles [13]. For example, the formation of vehicle platoons can increase road capacity and safety. In a platoon, a set of vehicles follow a leader with a small safety distance between them [14]. To keep the safety distance, the vehicles have to communicate with the others to anticipate acceleration and breaking. Also, there are several platoon activities that must be considered, such as allowing cars to join or to leave the platoon and defining safety distances [15].

In this context, we propose to simulate a scenario in which, in tandem with the transition from human-driven to autonomous vehicles, we will have a transition from regular to smart infrastructures. In the case of autonomous vehicles, we investigate here an infrastructure to enable the sharing of roads between human-driven and autonomous vehicles.

Fig. 1. Illustration of an AV platoon system.[3]

2.2. AV platoon system

The proposed system consists of autonomous vehicles traveling in platoons on exclusive lanes, achieving high efficiency through synchronization with traffic lights. The three main pillars of the system are:

1. Open data network: The city will provide a wireless local area network that vehicles could access to obtain traffic signals data. Traffic signals will follow carefully designed timing plans enabling almost uninterrupted progression of vehicle platoons. This is a scenario discussed recently in the literature with works proposing open traffic lights data [16] and trying to reduce city congestion using traffic signals coordination [17].
2. AV exclusive lanes on selected arterial roads: AVs using the system will have narrower dimensions so that a regular lane could fit two lanes of these vehicles. One of them will be an expressway dedicated to platoons, while the other one will consist of extra space for maneuvers. Examples of narrower vehicles are the Aurrigo pods[1] and 2getthere PRT.[2] These pods are not yet ready for urban environments, as they will require better engines and batteries. However, those two examples show that this type of vehicle is already being used today in specific scenarios.
3. Vehicle platoons: Vehicles using the system will have some automation level and organize themselves in platoons to maximize efficiency. The platoons use the open data network to travel through the traffic signal green waves, minimizing travel time and stops. Fig. 1 illustrates this configuration.

The system's main objective is to offer an option for urban transportation for the period when the fleet of AVs will be growing, allowing them to share the roads with conventional vehicles. For vehicles using the system, the travel time would be reduced, since there would be fewer stops due to traffic signals or traffic jams.

To fully realize this idea, there are several implementation decisions and definitions required. For example, the vehicle-to-vehicle and vehicle-to-infrastructure network protocols and technologies, the specific vehicle designs, the necessary level of vehicle automation, and AV platooning techniques. To enable a simulation of the proposed idea, we modeled the most relevant aspects that would impact vehicle flow and travel time, and abstracted away details that would have a smaller impact but, still, are essential for the success of such a system. Specifically, we made the following assumptions in our model:

1. We consider ideal conditions for vehicle-to-vehicle and vehicle-to-infrastructure communications; this is already a well-known problem well covered in the scientific literature [18] and beyond the scope of this paper. Our simulation model does not consider specificities of particular vehicular networks, and we do not propose or evaluate protocols or techniques for these communications to happen.
2. The exact design of vehicles is not specified. We do not propose or evaluate any vehicle design neither any engineering aspect necessary for vehicles to be able to use the system. We simply assume a length of 2.5 m, a body size already available in the market.
3. We consider perfect vehicle maneuvers to join or leave the platoons. We do not propose protocols nor evaluate individual vehicle dynamics. There is an extensive bibliography about platooning maneuvers [15,19,20].
4. We assume an average one-meter distance between the vehicles in the platoons. We do not consider string stability, a problem that can cause disturbances in the vehicle's distances, increasing the platoon size or causing traffic jams [21].

[1] https://aurrigo.com/devpod/.
[2] https://www.2getthere.eu/prt-vehicle-automated-taxi/.
[3] https://www.questtonomobility.com/english.

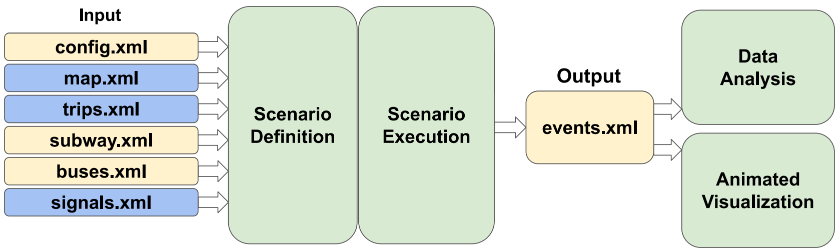

Fig. 2. InterSCSimulator components, inputs, and outputs. The blue inputs are the files modified for this work. *Source:* Adapted from [22].

5. We are not simulating possible problems that can destabilize the platoons, such as accidents and traffic light malfunctioning. These aspects could be incorporated in future versions of our model, which is open-source.

With these assumptions, we proceed to elaborate on how we simulated the AV system in different configurations.

2.3. InterSCSimulator

InterSCSimulator is an open-source, scalable simulator for large-scale smart city scenarios [22]. In its current version, the simulator provides mobility models for cars, pedestrians, buses, and the subway. Previous work shows that InterSCSimulator is capable of simulating, faster than real-time, an entire city such as São Paulo, with more than 10 million software agents virtually moving across tens of thousands of streets. The simulator is implemented in Erlang, a language suitable for developing highly parallel and distributed applications based on the actor model.

The InterSCSimulator has two main components: **Scenario Definition**, which receives the input files and creates the simulation scenario, and **Simulation Engine**, which executes the algorithms, models, and actors and generates the simulation output. For mobility simulations, it receives three required files as input: **map.xml**, with the city street graph, **trips.xml**, describing all the trips that must be simulated, and **config.xml**, with general options such as the total simulation time. When the simulation ends, it generates an output file with the events that occurred during the simulation.

We added new features for the development of the AV system model and made enhancements to the InterSCSimulator. In particular, we added support for the traffic signal synchronization and the indication of the roads that have AVs exclusive lanes. Fig. 2 presents the InterSCSimulator components and their inputs and outputs. The blue inputs were modified in this work. In the map, we added the AVs exclusive lane's information, in the trips included the platoons, and in the signals incorporated the synchronization mechanism.

The simulator uses a mesoscopic traffic model, in which the vehicles transverse each link with a constant speed v, defined at the instant that the vehicle enters the link. This speed depends on each link's characteristics and the number of vehicles crossing the same link at the moment. The relation between vehicle density and speed is based on Song et al. [23] and is defined as follows:

$$v = \begin{cases} v_{free} & \text{if } k \leq k_{min} \\ v_{free} * (1 - (\frac{k}{k_{jam}})^{\beta})^{\alpha} & \text{if } k_{min} < k < k_{jam} \\ v_{jam} & \text{if } k \geq k_{jam} \end{cases} \tag{1}$$

Where v_{free} is the speed limit in the link, usually dependent on road characteristics and traffic regulations; k is the current linear vehicle density in the link (in vehicles/m); k_{min} and k_{jam} are thresholds that classify each link as free ($k \leq k_{min}$) or jammed ($k \geq k_{jam}$); v_{jam} is the typical speed of vehicles in a traffic jam; and α and β are configurable parameters for the model calibration.

We use $k_{min} = 0.3$, $\alpha = 0.45$, $\beta = 1.0$ and $v_{jam} = 2.5$ m/s for all links. The values of α and β were selected as those better approximating average travel times obtained from real measurements. The value of v_{jam} was defined from real congestion speeds measured in the city of São Paulo.[4] Finally, k_{jam} is calculated as:

$$k_{jam} = \frac{n_{lanes}}{l_{cell}} , \tag{2}$$

where n_{lanes} is the number of traffic lanes in the segment that the link represents, and l_{cell} represents the length occupied by each vehicle in a jammed condition. For l_{cell}, we used the same value of MATSim simulator $l_{cell} = 7.5$ m [24].

Observe that the coefficient $\frac{k}{k_{jam}}$ in (1) can be obtained as

$$\frac{k}{k_{jam}} = \frac{c}{c_{jam}} \tag{3}$$

[4] CET — https://bit.ly/2MVIXzk.

where c is the current vehicle count at the link and c_{jam} is the maximum vehicle count that the link supports before being considered jammed. c_{jam} is calculated as

$$c_{jam} = n_{lanes} \cdot \frac{l_{link}}{l_{cell}} \tag{4}$$

where l_{link} is the length of each link, in meters.

The main change in the simulator for this work was the simulation of platoons. To add this feature, we considered each platoon as a very-long vehicle with associated meta-data. It occupies the total capacity of one or more entire links depending on the platoon and link size. Platoon size can vary during the simulation, allowing cars to join or to leave the platoon in any instant of the simulation as required by their trip origin and destination. In Section 4, we detail the platoon characteristics used in this work.

3. Related work

Previous research in the field can be divided into the simulation of autonomous vehicle systems, mostly evaluating the impacts of replacing HVs by AVs, simulation of vehicle platoons, showing how platoons can increase road capacity, and mixed-traffic, modeling the interaction between AVs and HVs.

3.1. Simulation of AV systems

There are many works simulating AV systems in different cities around the world. For example, Hörl [25] presents an extension to the MATSim simulator that allows the simulation of autonomous taxis. To test the extension, the author used a scenario with 84,000 people in Sioux Falls, USA, simulating car, taxi, bus, and walking trips. The author proposed a utility function based on price and waiting time. The results showed that with a fleet of 1000 AVs, the demand for this new service would be high, with more than 45% of the total trips and many people shifting from private cars and public transportation to the AV service.

Dia and Javanshour [26] present a model to simulate an AV on-demand service in Melbourne, Australia. The idea was that, instead of using private cars, passengers should use shared vehicles with a maximum waiting time of 5 min. The simulation showed that 247 vehicles could replace all the 2047 original private cars implying an 88% decrease in the number of running cars and reducing the required parking space by 83% with the stated waiting time. A downside was that the total amount of traveled kilometers increased by almost 10% due to empty trips that the vehicles perform to reach the next passenger.

Bischoff and Maciejewski [3] developed a simulation of Berlin that replaced all the private owned cars by autonomous taxis. The simulated scenario is based on a typical weekday. Their most important contribution is an algorithm to dispatch the taxis based on a demand–supply balancing [27]. The authors started the simulation with 50 thousand cars and increased it up to 250 thousand. The results showed that 110 thousand autonomous taxis could replace the city's 1.1 million fleet, with the average waiting time smaller than 3 min.

Alam and Habib [28] developed a simulation with shared autonomous vehicles (SAVs) in Halifax, Canada. The study considered the morning peak with 57.694 trips in the VISSIM simulator. Four scenarios were considered, with fleet sizes of 450, 900, 1800, and 3600 SAVs. The results showed that, in the first scenario, 15% of the trips were served with SAVs increasing up to 65% in the last scenario. Also, the simulation showed a decrease from 25% to 47% of trips in conventional cars. However, the study also showed an increase in travel times, and the total kilometer traveled because of the empty trips made by AVs.

All these studies evaluate the impact of AVs in the city. However, all have the same traffic models for AVs and HVs. The difference is only the behavior of the vehicles in the city.

3.2. Vehicle platoons

The idea of vehicle platoons was already simulated in different scenarios such as highway traffic and to test vehicle-to-vehicle communications. For example, Zhao and Sun [29] proposed a platform to simulate different maneuvers to the formation of vehicle platoons, such as adjusting, splitting, dismissing, and joining. The simulation results showed that the road capacity increased with more vehicles able to join the platoons. However, the simulated scenario was small, with only one straight road and not using real data to consider the total amount of vehicles to simulate.

Heinovski and Dressler [30] use an optimization model to evaluate the formation of platoons in a highway with centralized and distributed approaches. The centralized approach uses global information of all cars in the scenario, and the distributed approach only local information. The simulation was executed in PLEXE [31], an extension of the SUMO simulator for platoon formation. The scenario was a freeway with 30km, four lanes, and a flow of 2000 vehicles/hour. As the simulation was not a congested scenario, the travel time of the vehicles using the platoon increased using both approaches.

Table 1
Comparison of AV simulation works with our proposed model.

	Real Data	Platoon	Mixed Traffic	AVs Impact
[25], [28] [34]	X		X	X
[26], [3]	X			X
[29], [30]		X		
[36], [14]		X	X	
[32], [33]			X	
Proposed model	X	X	X	X

3.3. Mixed traffic

As the simulation described in this paper, some studies evaluate the mixed traffic conditions with Autonomous Vehicles and Human-Driven Vehicles. For example, Chen et al. [32] present a cellular automaton model in which the AVs know the speeds and positions of vehicles in front of it, and the HVs randomly decelerate. This study found that the AVs should know the status of at least five vehicles ahead to maximize the flow and that the HVs deceleration has a high impact on the general traffic. Liu et al. [33] also developed a cellular automaton model to evaluate the impacts of lane changes algorithms on mixed-traffic. In this model, the AVs can communicate with the adjacent AVs in the target lane to calculate the best moment to make the maneuver. The scenario used a three-lane highway and simulated different AV rates (0%, 40%, 80%, and 100%). The results showed that the road's maximum flow could increase from 2000 vehicle/hour to 3500, a more than 70% improvement.

Rezaei and Caulfield [34] present a mixed-traffic microsimulation in a motorway in Dublin, Ireland. The scenarios started with no AVs and increased its share by 10% until all vehicles being AVs. The simulation showed a great improvement in the traffic increasing the AVs share, specially reducing queue length and the number of vehicle stops. It also showed that 60% is the optimum AV share. Virdi et al. [35] evaluated the potential conflicts in intersections for different AV penetration rates. The results showed that low penetrations of AVs (20%) can increase the conflicts in signalized intersections, but reduce them in priority intersections (such as round-abounds), and for high penetration rates, all intersections can have a significant conflict reduction.

Some papers also simulate platoons in mixed traffic. Zhao et al. [36] described the use of vehicle platoons for mixed automated and human-driven vehicles at one signalized intersection to decrease pollution caused by vehicle acceleration. The authors developed an optimization model in which the AVs are the platoon leaders aiming to minimize fuel consumption with a small impact on the other vehicles' travel time. The model has the objective to control the speed of the vehicles to avoid them to stop because of red lights. The paper describes five simulation scenarios, with 20%, 40%, 60%, 80%, and 100% of AVs, and the results showed a considerable fuel consumption reduction from 20% to 60% and only a limited impact in the last two scenarios. The travel time decreased from the first to the second scenario and then stabilized.

Gong and Du [14] propose a cooperative platoon system with AVs and HVs. In their model, AVs have a standard smooth behavior and, using online learning, they predict the HVs behavior and adapt. The authors claim that soon there will be HVs within platoons of connected AVs. Numerical simulation showed that their algorithm could efficiently decrease the traffic oscillation propagation and stabilize the entire platoon flow.

All the works present positive impacts on the traffic flow due to the introduction of AVs in motorways or urban scenarios. However, they normally use a synthetic scenario, with a single road. In summary, we can see that several different urban and highway scenarios have been simulated in the literature, in general, showing significant benefits deriving from the introduction of AVs and platoons in mixed-traffic scenarios. To the best of our knowledge, this paper is the first that considers the very likely scenario of AV platoons sharing the roads with conventional cars in a realistic, large urban area. Most of the related works that simulate platoons use small or synthetic scenarios in microsimulations with a few cars in a small area. In our case, we simulate the behavior of a major artery in a real city with thousands of vehicles. This paper is also unique in the independent analysis of the impact of each change from the current situation to the final complex scenario we simulate. Although the traffic of AVs and HVs are segregated in our study, it shows how the increase of the AV fleet can positively impact the HV traffic.

Table 1 compares the related works with our simulation regarding the type of data (generated or real), whether it simulates platoons and mixed-traffic, and whether it measures the impacts of AVs vehicles in the cities.

4. Simulation model, parameters, and scenarios

We simulated different scenarios to understand the impact of all changes proposed by the AV system. First, we simulate (*i*) the current configuration of the Avenue; then, we simulate (*ii*) exclusive lanes for autonomous vehicles, (*iii*) smaller autonomous vehicles, (*iv*) AV pods platoons, and, finally, (*v*) the synchronization with the traffic signals.

We used the first scenario as a baseline to evaluate the improvement/deterioration in each of the subsequent scenarios. The Paulista Avenue is a two-way road, 2.8 kilometers long, with four lanes in both ways (one used mainly by buses), and 13 signaled crossings. The Avenue is a major arterial road that connects the West, East, and South regions and is one of the city's main landmarks. Fig. 3 presents the Paulista avenue position in São Paulo, and Fig. 4 details the current configuration and shows the position of all traffic signals in the Avenue.

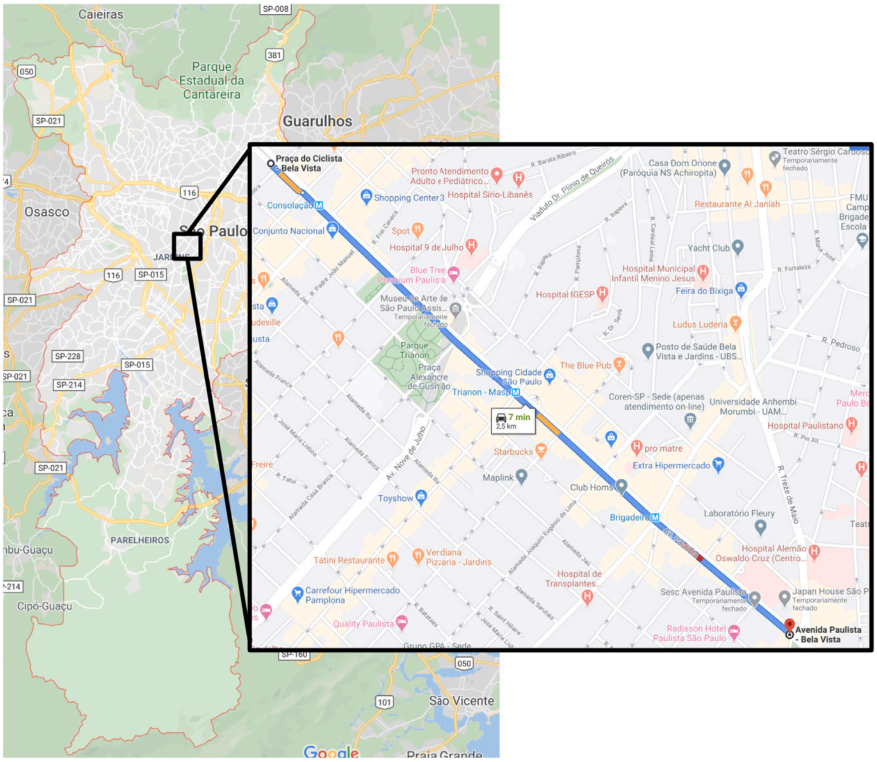

Fig. 3. Paulista avenue in the city of São Paulo.

Fig. 4. Tile from OpenStreetMap showing the selected segment of Paulista Avenue, the location of traffic signals and the points of origin and destination for the simulated trips.

We manually measured the traffic signal duration on the ground in the morning peak hour (8 am).[5] The intervals were different for all the crossings, but all have a complete cycle of approximately 130 s (green + red). As Paulista Avenue has heavier traffic than all its crossing roads, its green intervals last longer. Table 2 shows the measured phase duration for all traffic signals of the avenue along with the name of the crossing road. We are not considering the amber phase, as it does not affect our mesoscopic traffic model's travel time. We divided the amber time as half red, half green.

To generate the simulated traffic in the avenue, we used a uniform distribution based on the official vehicle count per hour of São Paulo's Traffic Engineering Company (CET).[6] This government's data show that the number of vehicles in the morning peak hour is 2349 in the Paraíso way and 3060 in the Consolação way. In our simulation, 50% of the vehicles start and end at the avenue extremities. The other 50% randomly begin and finish their travels in the avenue crossings.

In the second and third scenarios, we added the AVs to the simulation to evaluate their impact in the Paulista Avenue traffic. Also, we included the AV exclusive lane, decreasing the total avenue capacity for conventional cars. In the second scenario, we considered AVs having the size of current conventional cars and simulated ratios of AVs to conventional cars starting from 0% of AVs and going up to 100% of AVs, increasing in steps of 5%. We assumed that the capacity of the AV lane would be 10% larger

[5] Signal timing typically changes during the day, but it stays fixed during the morning rush period.

[6] CET — https://bit.ly/2MVIXzk.

Table 2
Traffic signal duration for Paulista Avenue during morning peak hour. The number in parentheses refers to the signals in Fig. 4.

Crossing	Green	Red
Bela Cintra (1)	68s	61s
Haddock Lobo (2)	85s	43s
Augusta (3)	83s	41s
Min. Rocha Azevedo (4)	83s	48s
Peixoto Gomide (5)	85s	46s
Al. Casa Branca (6)	89s	43s
Pamplona (7)	83s	46s
Al. Campinas (8)	76s	55s
Joaquim Eugênio de Lima (9)	78s	53s
Av. Brigadeiro Luís Antônio (10)	78s	62s
Carlos Sampaio (11)	99s	34s
Teixeira da Silva (12)	80s	50s
Praça Oswaldo Cruz (13)	80s	50s

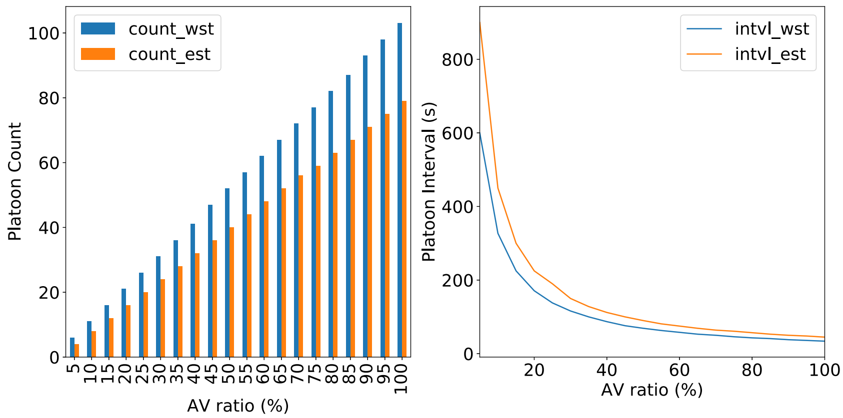

Fig. 5. Total count of platoons and departure interval for all AV pods ratio in both avenue directions.

than the one for conventional cars because AVs should be able to use the avenue space better, decreasing the space between cars, avoiding shock-wave formation and propagation and presenting fewer acceleration jitters than human drivers [37,38].

In the third scenario, as the main change, we considered that all autonomous vehicles are small, which is one of the characteristics of our proposal, as the cars in the platoons are pods with approximately the size of a Smart Fortwo vehicle (2.5 m), approximately 40% smaller than a conventional car. To avoid confusion, we call them AV pods. We used the same AV ratios from the previous scenarios. Concerning scenario 3, the exclusive lane's capacity here is 50% larger than the one for the regular lanes, 10% already added in scenario 2 plus 40% due to the smaller vehicles.

In the fourth scenario, we added the vehicle platoons for AV pods, which increases the capacity of the AV exclusive lane. We considered platoons of 25 vehicles and distributed the departures from the start of the Avenue based on the number of vehicles able to join it.

Fig. 5 presents the number of platoons and their intervals in seconds to the different AV pods penetration rate in each of the avenue directions (Eastward — Paraíso way and Westward — Consolação way), from 0% to 100% of AV pods. Also, the AV pods that start their trips from other points of the Avenue can join the platoon if they find one during their trajectory and leaves the platoon just before reaching the point in which they leave the Avenue to make a turn. A limitation of our current model is that it is not considering the time to join or leave the platoon, which can have a small impact on the total travel time.

Internally, in the simulator, we considered the platoon a vehicle that can change its size, when new vehicles join or leave the platoon. The size of the platoon is calculated using the following equation:

$$platoon\_size = number\_of\_vehicles * (vehicle\_size + safety\_distance) \tag{5}$$

The considered AV size is 2.5 m, and the safety distance is 1 meter [39]. Each platoon starts with 25 vehicles, and its maximum number of vehicles is 30, allowing new vehicles to join it during the travel. The assumption that the maximum platoon span is 105 m. It is important because it will impact the minimum time that a traffic signal must be open for an entire platoon to cross a signaled crossing.

Finally, the fifth scenario synchronizes the platoons with the traffic signal avoiding that the platoons stop at traffic signals. The method we used to create the timing plan is explained in Section 5. Table 3 shows the traffic signal timing for Scenario 5; the complete cycle (green + red) has approximately 90 s. The optimization is calculated offline, and we use the same timing during all

Table 3
Phase duration of all the traffic signals in the Paulista Avenue crossings optimized for the platoons.

Crossing	Green	Red
Bela Cintra (1)	45	40
Haddock Lobo (2)	45	23
Augusta (3)	45	22
Min. Rocha Azevedo (4)	45	26
Peixoto Gomide (5)	45	24
Al. Casa Branca (6)	45	22
Pamplona (7)	45	25
Al. Campinas (8)	45	33
Joaquim Eugênio de Lima (9)	45	31
Av. Brigadeiro Luís Antônio (10)	45	36
Carlos Sampaio (11)	45	16
Teixeira da Silva (12)	45	28
Praça Oswaldo Cruz (13)	45	28

the simulation. Again we are not considering the amber phase. Moreover, the optimization model that we are using also does not consider the amber phase.

5. Traffic signal timing plan

To proceed with our evaluation of the AV system at Paulista Avenue, we developed a traffic signal timing plan that enables vehicle platoons to move in both directions across the entire avenue without stopping at red lights. Such a timing plan can be formulated as an optimization problem, as presented by Little et al. [40]. This optimization problem aims to find offsets for maximal vehicle bandwidth given cycle time, red times, signal distances, and street speed.

In this formulation, the two opposite directions in which the platoons travel are called inbound and outbound. All traffic signals have the same cycle time. The following notation is used, in which quantities with bars refer to the inbound direction, while the ones without bars refer to the outbound direction:

- $b[\overline{b}]$: bandwidth for the outbound [inbound] direction, measured in cycles;
- S_i: ith traffic signal, $i = 1 \ldots n$: Traffic signals are numbered from 1 to n in the outbound direction;
- $r_i[\overline{r}_i]$: outbound [inbound] red time at S_i, in cycles;
- $w_i[\overline{w}_i]$: time to the outbound [inbound] green band arrive in the traffic signal S_i after it opens. Measured in cycles.
- $t(h,i)[\overline{t}(h,i)]$: travel time from S_h to S_i outbound [S_i to S_h inbound]
- $\phi(h,i)[\overline{\phi}(h,i)]$: Time from the center of an outbound [inbound] red at S_h to the center of a particular outbound [inbound] red at S_i. The two reds are chosen so that each one is immediately to the left [right] of the outbound [inbound] green band. The sign is positive if the center of the red in S_i lies to the right [left] of the center of the red in S_h. Measured in cycles.
- Δ_i: Time from the center of a given $\overline{r}_i$ to the nearest r_i. The sign is positive if the center of r_i is to the right of the center of $\overline{r}_i$. Measured in cycles;
- $\tau_i[\overline{\tau}_i]$: Queue clearance time for the outbound [inbound] bandwidth upon leaving S_i; Measured in cycles;

The authors also combined two equations expressing the time difference, measured in cycles defining the quantity $m(h,i)$:

$$m(h,i) = \phi(h,i) + \overline{\phi}(h,i) + \Delta_h - \Delta_i \tag{6}$$

To simplify the notation, the following definition is used:

$$x_i = x(i,i+1) \quad \text{for} \quad x = t, \overline{t}, m, \phi, \overline{\phi} \tag{7}$$

A timing plan for the traffic signals can then be obtained by solving the following mixed-integer programming problem:

$$\begin{aligned}
&\text{Find} \quad b, \overline{b}, w_i, \overline{w}_i, m_i \quad \text{to} \\
&\max \quad b \\
&\text{s.t.} \quad \overline{b} = b \\
&w_i + b \leq 1 - r_i, \quad i = 1 \ldots n \\
&\overline{w}_i + \overline{b} \leq 1 - \overline{r}_i, \quad i = 1 \ldots n \\
&(w_i + \overline{w}_i) - (w_{i+1} + \overline{w}_{i+1}) + (t_i + \overline{t}_i) + \\
&\Delta_i - \Delta_{i+1} = (-1/2)(r_i + \overline{r}_i) + (1/2)(r_{i+1} + \overline{r}_{i+1}) + \\
&(\overline{\tau}_i + \tau_{i+1}) + m_i, \quad i = 1 \ldots n-1 \\
&m_i = \text{integer} \\
&b, \overline{b}, w_i, \overline{w}_i \geq 0, \quad i = 1 \ldots n
\end{aligned} \tag{8}$$

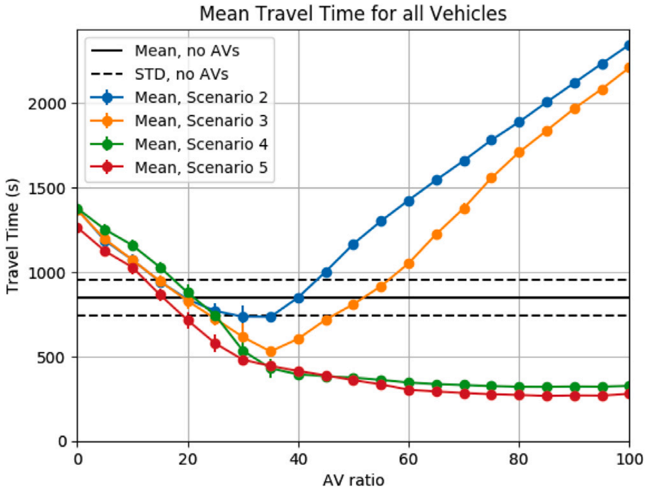

Fig. 6. Comparison of travel time in the simulation scenarios considering the different AV ratios for all vehicles in the simulation.

In the case of DR, we made the following assumptions:

1. The red times for the inbound and outbound directions are aligned in every S_i, meaning that $\Delta_i = 0$ for $i = 1 \ldots n$
2. Since the platoons will not stop at the traffic signals, there is no need for queue clearance time, so $\tau_i = 0$ and $\overline{\tau}_i = 0$ for $i = 1 \ldots n$

Applying these assumptions, the mixed-integer programming problem becomes:

$$
\begin{aligned}
\text{Find}\quad & b, \overline{b}, w_i, \overline{w}_i, m_i \quad \text{to} \\
\max\quad & b \\
\text{s.t.}\quad & \overline{b} = b \\
& w_i + b \leq 1 - r_i, \quad i = 1 \ldots n \\
& \overline{w}_i + \overline{b} \leq 1 - \overline{r}_i, \quad i = 1 \ldots n \\
& (w_i + \overline{w}_i) - (w_{i+1} + \overline{w}_{i+1}) + (t_i + \overline{t}_i) = (-1/2)(r_i + \overline{r}_i) + \\
& (1/2)(r_{i+1} + \overline{r}_{i+1}) + m_i, \quad i = 1 \ldots n-1 \\
& m_i = \text{integer} \\
& b, \overline{b} \geq 0, \quad i = 1 \ldots n
\end{aligned} \tag{9}
$$

We used the latter formulation with `lp_solve`[7] to obtain timing plans with the cycle times of 60, 90, 120, and 150 s. The plan with a cycle of 90 s had the largest bandwidth measured in vehicles per hour and is used in the rest of this paper.

6. Simulation results

To evaluate the impact of AV system on travel time, we simulated each scenario described in Section 4. We also compared the travel time of each scenario with the benchmark. Fig. 6 shows how the average travel time for all vehicles (AVs, AV pods, and non-AVs) evolves as we consider different ratios of AVs to non-AVs in each simulation. The black line presents the mean travel time for the baseline scenario, and the dotted line shows the standard deviation. We executed each scenario ten times using different random travels using uniform distribution to generate the start travel time and location.

The first and second scenarios follow the same pattern: with few autonomous vehicles, the travel time is higher than in the baseline scenario. Then, with 25% to 50%, the travel time is shorter than the baseline, and finally, from 50% and up, the travel time starts to increase quickly. The explanation for this behavior is that, with few AVs, there are roughly the same amount of human-driven vehicles with one less lane; on the other hand, with more than 50% of AVs, the exclusive lane becomes very congested.

The fourth and fifth scenario starts with the same pattern, with the travel time decreasing when the AV ratio is smaller. The difference is when the ratio is larger than 40%, in Scenarios 2 and 3, the travel time starts to increase. However, in Scenario 4 and 5, the time stays almost the same from after 40% of AVs. Even with all vehicles using only the exclusive lane, the mean travel time

[7] http://lpsolve.sourceforge.net/5.5/.

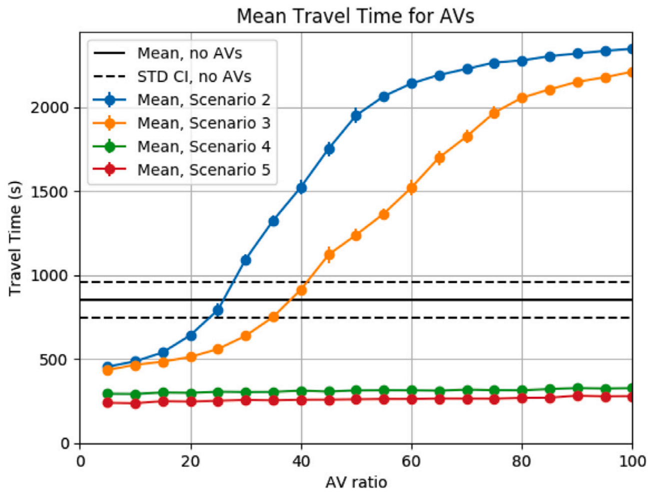

Fig. 7. Comparison of AV travel times considering different AV ratios.

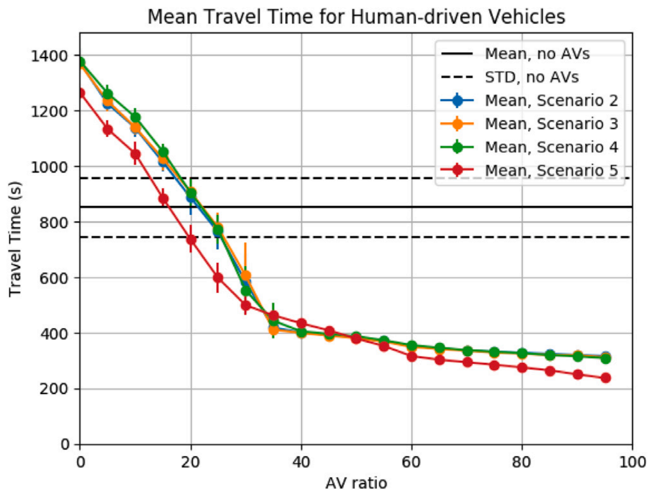

Fig. 8. Comparison of travel time in the simulation scenarios considering the different AVs ratios only for human-driven vehicles.

in Scenarios 4 and 5 is much smaller than the baseline. This shows the impressive result that just one lane could handle Paulista Avenue's entire traffic in the morning peak hour.

The fifth scenario had better mean travel time, even with less than 20% of AV pods. The explanation of this behavior is the synchronization of the traffic signals, which improved the travel time for all vehicles.

The AVs results (see Fig. 7) for Scenarios 2 and 3 follow the same pattern, but Scenario 3 has shorter travel times. The cause of this behavior is that with more AVs, the exclusive lane became very congested; as in Scenario 3 we considered AV pods, smaller than a regular car, the road capacity is 40% larger. The exclusive lane supports more cars until it gets congested. This result shows that even with AV pods, the AVs will only significantly impact the overall travel time if they either remove human-driven cars from the streets or use better control algorithms that enable platooning.

In Scenario 4 and 5, in which the AV pods move in platoons, the travel time increased very slowly with more vehicles in the exclusive lane. This result shows that the lane capacity with the platoons is much larger than in the other scenarios. The new traffic signal timing plan further improved the mean travel time for the platoons, since they never stop in a red light in this scenario. The impact of the new signal timing plan was significant but modest because the semaphores in the Paulista Avenue are already programmed to allow green waves for HVs. This overall result shows that a control algorithm can have a substantial impact on city traffic.

The results for the human-driven vehicles are almost the same in all the scenarios, as depicted in Fig. 8. The explanation for this behavior is that, with more AVs, less conventional vehicles are in the other lanes. Therefore, the traffic starts to flow better and gets closer to the free-flow speed. The chart shows a considerable decrease until the scenario of 35% of AVs, and then it decreases slowly because the traffic is already almost free. Only Scenario 5 has a better mean travel time because of the traffic signals synchronization.

Table 4
Best average travel time in each scenario and corresponding optimal AV penetration rate.

Scenario	Travel Time	AVs Penetration Rate
Baseline	850	0
Scenario 2	734	35
Scenario 3	529	35
Scenario 4	321	95
Scenario 5	268	95

Table 4 presents the best average travel time and the AV penetration rate for this case in all scenarios. The numbers show that the largest impacts were observed when going from Scenarios 2 to 3 and Scenario 3 to 4. Therefore, the largest impacts of the AV system are the smaller cars and the platoon formation, which can increase the capacity of the AVs' exclusive lanes. The traffic signal synchronization also had a positive impact on traffic flow. Our results confirm past studies that showed that vehicle platoons could increase lane capacity two or three times [41].

To assure the reproducibility of our research results, all of the source code, input, and output data, as well as the scripts to generate the graphs, are publicly available in our GitHub repository.[8] This material also enables other research groups to build on top of our work easier, and we will happily assist researchers interested in using our materials in the spirit of open science.

7. Discussion and limitations

Autonomous Vehicles will likely radically change urban mobility within the next two decades. However, as the results of scenarios 2 and 3 showed, only replacing human-driven vehicles by AVs or AV pods might not be sufficient to solve traffic problems. Better controls and coordination algorithms, such as those enabling platoon formation, will significantly improve city traffic. In addition to platooning, other procedures could be used in a system like DR, such as re-routing, dispatching, and dynamic speed control in case of traffic problems.

In this paper, we focused on analyzing the travel time to cross the entire Paulista Avenue in São Paulo, Brazil. Nevertheless, improving the traffic will bring other benefits to the city, such as reducing air and sound pollution; as vehicles stop and accelerate less often, they emit fewer pollutants and produce less noise. Another significant result is that in a scenario with full transition to AV, just one lane could handle all the avenue traffic. Thus, substantial space can be given back to the city for other purposes such as leisure and green spaces, which are scarce in a metropolis such as our case study, São Paulo.

Our work's most important limitation is that we are not considering potential problems that the AV system will face in a real city. For example, we are not simulating car crashes or malfunctioning and also not considering the possibility of pedestrians jumping in front of vehicles accidentally. These events would probably have a significant impact in the AV exclusive lane, mainly in the scenarios in which the interval between platoons is small. Also, we are not simulating potential problems with the platoon formation; control algorithms might fail, and a car might spend some time to synchronize with the platoon. In fact, the mesoscopic model of the InterSCSimulator is not able to simulate microscopic details of maneuvers such as joining and leaving the platoon.

Another important aspect that our mesoscopic model does not consider is string stability [21]. It can be caused by different platoon operations such as vehicles leaving or joining the platoon or problems such as vehicle malfunction, accidents, and communication failures. For example, simulations using the microscopic simulator SUMO showed that vehicles must accelerate and decelerate to maintain the desired safety distance, impacting the overall speed and throughput of the platoons [20]. Finally, we are not considering network problems in Vehicle-to-Vehicle and Vehicle-to-Infrastructure communication. Indeed, more research is required to develop new control algorithms and better simulate AVs' impacts with even more realistic models.

8. Conclusions and future work

In the near future, autonomous vehicles will share the road with human-driven vehicles in many cities worldwide. The communication and synchronization capabilities of AVs can leverage the capacity of the roads, improving traffic conditions. For example, AVs can function with a smaller safety distance between them, and they can form platoons dynamically. This paper presented the simulation of DR, a proposed AV system that enables the co-existence of AVs and human-driven cars.

The system's main elements are an AV exclusive lane, small cars, platoons, and synchronization of the platoons with the city traffic signals. We simulated each of these elements incrementally to assess the impact of each change. The results showed that the sole transition to AVs, even of small size, would not change the existing traffic patterns significantly. However, control algorithms, such as the formation of vehicle platoons, can dramatically increase the capacity of the city roads. Our results showed that with an AV penetration ratio higher than 40% and with the ability to form platoons, the travel time in Paulista Avenue could be 50% shorter than in the current situation, benefiting tens of thousands of people and decreasing the environmental impact.

A large amount of R&D is still required before a system such as the described in this paper becomes a reality. Specifically, concerning the work presented in this paper, there are multiple paths for improving our simulation and models:

[8] GitHub repository — https://github.com/ezambomsantana/dr_analysis.

- The extension of the simulation to a larger city area covering all the main arterial avenues. Then, measuring the system impact for long trips while simulating different control algorithms. A difficulty of this work would be to simulate all the semaphores of the larger region with a good degree of fidelity to reality.
- Designing a microscopic simulation to understand the impact of the vehicle maneuvers while joining and leaving the platoons. This work could also be used as a basis to improve the mesoscopic model used in this paper.
- Using different routing algorithms throughout the city considering the exclusive lanes and platoons. In a scenario with a large network, we could evaluate different routing strategies that take the exclusive lanes into account and their effects on the city's overall traffic.
- Communication protocols: The original formulation for the AV system states that some communication among vehicles and infrastructure is necessary. It would be interesting to develop the required protocols and study their performance and scalability with simulations.
- Simulating potential problems in the platoons such as vehicle mechanical failures, crashes, and network instability. In this case, the AVs might have to use the normal lanes to pass blocked parts of the exclusive lane. This will affect the travel time of all vehicles.

This paper brings new insights into the future of AVs and discusses the likely scenario in which AVs will share the road with conventional vehicles. This paper included that AVs will bring multiple benefits to our cities in the future. However, there is still a long research and development path that must be covered before this scenario becomes a reality. Compared to other studies in the field, we add more evidence that simply replacing HVs with AVs will not solve the traffic problem in congested metropolises such as São Paulo. Also, we showed that control algorithms, such as AV platoons, could significantly impact positively the traffic in a real urban environment. Finally, our simulations show the incremental benefits of each change to the existing configuration in a systematic way.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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