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Simulating platooned connected autonomous vehicle in a large scale urban scenario

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Abstract

This article is concerned with the performance evaluation of connected, autonomous vehicles (CAVs) in a realistic large-scale microsimulation scenario. In particular the ques-tion is: how much could a high diffusion of CAVs possibly change (1) the average travel speeds (2) the trip times of all traffic participants, including pedestrians, and (3) the en-ergy/fuel consumption? For this purpose, admittedly favourable assumptions are made: a 100% diffusion of platooning-capable CAVs as substitution for private cars as well as a high maximum speed of platooned vehicles in order to enable platoon formation. The morning rush hour scenario of the metropolitan area of Bologna, Italy has been selected for assessment. This scenario, which has been created and validated in previous works, represents an activity based demand model with travel plans for individual citizens, in-cluding all relevant transport modes. The microsimulation is performed by means of the SUMO simulator. The entire demand has been generated with the SUMOPy tool. For the platooning of CAVs, SUMO's SIMPLA module has been used, which controlls the vehicles via the interactive TRACI API.

Results show an increased speed and reduced travel time for CAV vehicles, with respect to human driven cars, in particular in the periphery and less in the center with a dense road network. However, the reason for improved speeds and travel times is predominantly the higher maximum speed allowed for vehicles trying to catch up and join a platoon. Furthermore these higher speed would also be resposible for an increase in fuel consumption of approximately 5%.

In conclusion, CAVs alone are unlikely to reduce congestion in an urban area. To make the platooning concept work, additional technology and infrastructure is required in order to merge platoons effectively at freeways and at traffic lights. The latter could be simulated with GLOSA

Contents

1 Introduction

Micro-simulating realistic, large scale urban areas is challenging, when considering all modes of transport, including pedestrians and public transport [9]. Nevertheless, the performance assessment of connected, autonomous vehicles (CAVs) necessitates a microscopic simulation approach, especially when it comes to platooning. As stated in [6]: "macroscopic studies only consider traffic average parameters, this micro approach is initially more logical to study cooperation between vehicles, to define optimal gaps and speeds, etc". With *platooning*, vehicles are bunched together in trains, where headways between vehicles inside a platoon are shorter than what is achievable with human driven cars. The first vehicle of a platoon is called the leader while all the others are follwers. Vehicles trying to join the platoon are called catchup-followers. It is obvious that the catchup-follower vehicle needs to drive faster than the platoon in order join it.

The simulation of the formation and dissolution of platoons requires a sufficiently detailed modeling of the position, speed and acceleration of vehicles on the one hand as well as the knowledge of the vehicles routes. The vehicle route, which is decided based on link travel times is used to decide whether vehicles form a platoon or not. This means that there is a strong inter-dependency between microscopic events and macroscopic quantities (routes, flows and link speeds), suggesting that a separation between local microscopic simulations and large-scale macroscopic models would give unrealistic results.

The previously cited article also motivates the use of platooning for CAVs: if autonomous vehicles were to run individually, then they would actually decrease capacity because autonomous vehicles drive less agressive and have therefore larger headways than human driven vehicles. In addition, new travel demand is expected to generate as the potential user group of autonomous vehicles is considerably larger than the one able to actively drive a conventional car. For this reason, vehicle cooperation and in particular platooning is needed to offset or reverse these negative effects on the capacity.

The capacity increase of vehicle platoons depends on many inter-related factors, such as

- the platoon length
- achievable headway between vehicles within one platoon
- the effective time gaps between platoons
- the platoon duration, or variation of its length
- the platoon formation

While a vehicle driving as part of a platoon, an on-board distances control system allows short headways to the car in front, based on the distance and speed of both vehicles. Both quantities can be transmitted vai V2V communications or directly measuremented via Radar, laser or optical devices. Headways within a platoon are typically sub-second and are considerably short compared to what human drives are able to achieve. The distance control system is designed to satisfy multiple requirements during all possible speed transitions [2] : safety, string stability and comfort. Concerning safety, there are different *vehicle spacing policies.* The relevant policies are the *constant time headway policy* and *constant safety policy.* The constant time headway policy offers a constant, speed independent carrying capacity [12]. However, collisions can theoretically occur at higher speeds. Despite this drawback, constant safety considerations have been the headway policy for the design of linear control system for platoon-join manœvers [4]. Fewer literature can be found on feedback controllers that follow the constant safety separation policy. A constant safety controller needs by definition a nonlinear, quadratic feedback and does therefore not fit into concepts of standard linear control theory. A common approach to overcome this difficulty is the separation into a "safe trajectory generator", driving a linear feedback controller [4, 13]. An alternative, with a non-linear control-feedback has also been proposed [7]. Concerning string stability, it is required that the speed changes of the platoon leader are not amplified by the following vehicles. In case of linear controller, string stability can be proven easily [12]. The design of a non-linear feedback controller providing string stability is more complex, but also possible, for example by means of the Popov criteria [**?**]. A critical issue for the string stability is the time delay of the communication or measurement devices: a delay between an the occurance of speed-change of the lead vehicle and the moment when the follower vehicle recognizes it, is crucial to string stability. A large delay is typically jeopardizing string stability. V2V communication for position- and speed communications is typically faster than measuring via radar. If the leader communicated its speed and position to all followers simultaneously, the string stability would also be guaranteed. The issue regarding the inter-platoon space depends on many factors: a basic requirement for lasting platoons is obviously that all vehicles in a platoon have a common route, at least in part – the shorter this common route the the lower is the time vehicles stay together is a platoon. The ability for CAVs to join a platoon depends also on the provided infrastructor. For example extra lanes or ramps to accelerate the vehicle before joining the platoon. Concerning comfort criteria, it is necessary that the control system of CAVs incolved in a platoon guarantees also speed, acceleration and jerk limits.

Concerning the capacity increase, one needs to distinguish between ideal environments and real environments (urban environments in the present article). Shladover, (2012) [11] who has micro-simulated CAVs on a one-lane, intersection-free highway at steady-state traffic flows, has shown an 80% increase in capacity, assuming all vehicles are CAVs. However, micro-simulating CAVs in an urban environment with random trips results in much lower capacity gains of approximately 16%, due to the network-level effect [5]. Clearly, the dynamics in intersections and the durations of platoons appear to have a significant effect on the capacity [3].

Apart from the performance of the CAVs themselves, there is the question on the impact on other road users. One particular issue is the interaction with pedestrians on mixed access roads or at pedestrian crossings, where the average travel speed may reduce for both, pedestrians and C, dependent on the vehicle flows and pedestrian flows. Changes in travel time will in turn change demand and consequently flows of vehicles and pedestrians. See [15] for gap acceptance of pedestrians crossing a road with platooned CAVs.

These examples suggest that, in general, small, microscopic and large-scale macroscopic models cannot be simulated separately, which means only a large-scale microscopic model will ensure that microscopic dynamics will correctly determine the traffic flows and vice versa, thus global, network-level effects needs to be taken into account.

For these reasons, the present work evaluates the performance of platooned CAVs with a large-scale micro-simulation scenario with a realistic demand, including all relevant modes of transport. The next section describes some details about the methods and used parameters, while section 3 presents and discusses the results. Section 4 draws the main conclusion and points to limitation and potential future research.

2 Methods

This section is separated in two subsections, where the transport scenario and the CAV and platooning related aspects are explained.

2.1 The microsimulation scenario

The used validated microsimulation model for the medium size city of Bologna, Italy, with approximately 500,000 inhabitants is explained in detail in [9]. The entire demand has been created through the tool SUMOPy [8] while the simulation itself is performed by the SUMO simulator [1]. in brief, the road network of Bologna city has been converted from OSM to a SUMO XML format by SUMO's "netconvert" program and edited manually with SUMOs "netedit" . In addition, connectivity problems have been identified by matching GPS traces to the network. Traffic lights are an OSM node attribute, but the signals have been generated by heuristics. Large traffic light systems in and around the center have been edited manually based on traffic light plans provided by the city of Bologna. The road-network of the city of Bologna with surrounding towns is the core simulation area, covering approximately 50 km^2. The core area has a detailed street network, including bikeways and footpath. The entire metropolitan area of Bologna covers a wider area of 3.703 km^2. Figure 1 shows the traffic assignment zones (TAZs) of the core area from the 2001 national population census. As there is a substantial traffic between the core simulation area and the extra-urban TAZs, the citys road network has been manually expanded by a simplified road network – using again SUMO's netedit and satellite imaginary.

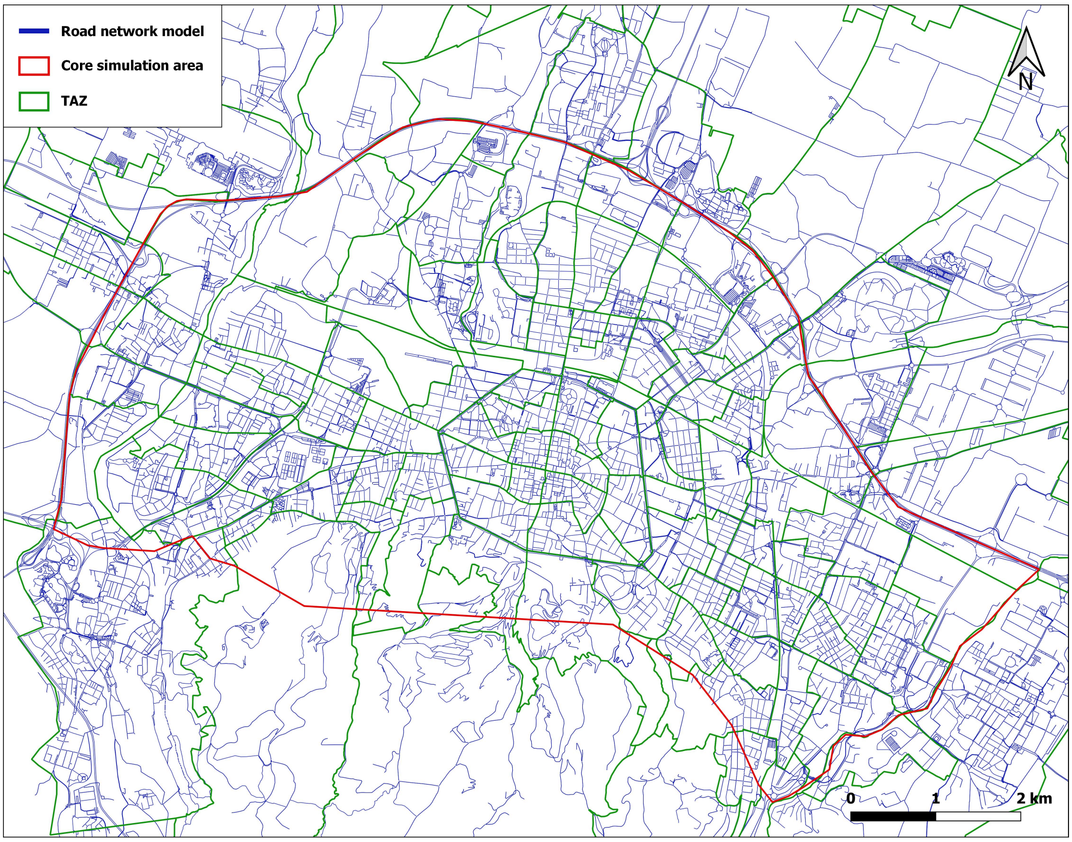

Figure 1: Bologna core network with TAZ.

The total number of road links is 32,409 with a total length of 3,316.20km. The share of major road (with priority level greater 7) is 20.11% of the total length or 667.05km. Moreover, there are 59,218 link connections and 14,724 intersections, 530 of which are regulated by a traffic light. The geometric shapes, heights and type of 58,421 buildings in the core simulation area have also been imported from OSM. Buildings are associated with activity locations of persons in the synthetic population model. In addition, on-street parking lots have been created with some heuristics along suitable roads.

The entire public transport service provided by the local operator (Tper) has been realistically modelled within the core simulation area by generating bus lines based on data from GTFS (General Transit Feed Specification). More specifically, 234 bus lines have been imported from GTFS for a workday in May 2018 during the time from 6:00 to 9:00 a.m. The service frequency has been averaged for this time interval for modeling purposes.

Demand has been generated mainly by disaggregating origin-to-destination matrices (ODMs) valid for a work-day from 7:00 to 8:00. In particular, a virtual population has been created by disaggregating OD-flows to single buildings, while taking their volume into account [10]. ODMs of the modes car, scooter, bus and walking has been used to generate the population, but only for demand flows between TAZs inside the core simulation area. Bicycle demand has been estimated from GPS traces recorded by citizens on a volunteer bases using Smartphone. Each GPS trace describes the movements of each participating cyclist through a sequence of time-stamped and geo-referenced Lat/Lon locations. For the used scenario, GPS traces recorded during the European Cycling Challenge campaign in Bologna in May 2016 have been used. The GPS traces have been filtered and mapmatched to create bicycle routes as a sequence of network edges. Only traces during rush hours have been relevant, more precisely between 8:30 and 10:30 a.m. The number of GPS trips need to be scaled to the effective number of trips, using a scale factor from a previous publication [59]. Also each GPS trace has been associated with a building, by analyzing the terminal GPS points.

At this point the assumed home and work location is defined for each person, and also a "preferred" mode of transport has been associated with each person, depending on the type of ODM or bike in case of GPS-generated persons. Next, plans have been created for each person, connecting the building of home with work activity and by involving the preferred mode. Afterwards some relaxation and calibration has been applied in order to achieve a higher consistency between mode choice and building location.

An external car demand (cars with origin or destination outside the core area) has been created by disaggregating ODMs on edges, considering all OD flows between external zones and zones inside the core area as well as external to external zones that are crossing the core area. With this method, external ODMs have been created for the modes car, scooters. External demand for bicycles have been created from again from GPS traces, following the same selection strategy as used for the OD flows.

Finally the dynamic user equilibrium has been determined for the scenario, optimizing the plans of the virtual population the trips of the external demand components.

2.2 Implementation of CAVs

The demand for CAVs has been generated by simply substituting all car trips with vehicles controlled by the algorithms of the SIMPLA [14] module through TRACI. SIMPLA is deciding over platoon join maneuvers, but it is not controlling the distances between vehicles. Instead, the distances are controlled by the car follower algorithm that can be specifies as a vtype in SUMO. The follower algorithms of can be dynamically changed at any time via Traci. This is necessary, for example if the vehicle changes from follower to leader or vice versa. Parameters of follower algorithms in normal/leader and follower/catchup mode are summarized in Table 1. The speed factor for catchup vehicles is set to two, which means CAVs could go as much as twice the speed to catch up with the leader. This high number is needed to allow a reasonable platoon formation within short distances. The default vehicle model is the standard Krauss model while during platoon operations the Shladover CACC model is used. Platoon update

Table 1: Vehicle type attributes of leader/normal and follower/catchup.

Attribute	value as leader/normal	value as follower
Length $[m]$	4.3	
Width $[m]$	1.8	
Height $[m]$	1.5	
Passengers	1	
Capacity	4	
Max. speed $[m/s]$	50	
Speed factor	1.0	2
Speed dev.	0.1	
Speed mode	7	1
Max. accel. $[m/s^2]$	2.9	5.0
Max. decel. $[m/s^2]$	3.0	
Emergrncy decel. $[m/s^2]$	8.0	
Reaction $[s]$	0.8	0.2
Driver	0.5	0
Min. gap $[m]$	1.0	0.3
boarding time $[s]$	4	
loading time $[s]$	4	
vClass	passenger	
Emission type	average passenger car (all fue types)	
Impatience	1.0	

time has been set to 2s, platoon gap equals 15m, platoon split-up time is 3s, and catchup distance equals 100m. As there were frequent congestions due to deadlocks at roundabouts and successive intersections, two SIMPLA underwent two modifications: A vehicle would not change from normal to follower mode unless

- the common route between the vehicle and the potential leader have at least a minimum distance (default is 500m)

- the common route between the vehicle and the potential leader have at least a certain number of edges in common (default is 3)

With these modifications deadlocks on networks with a high node density have been entirely avoided. However, it has been observed that SIMPLA works only with the standard lane change model, not with the sublane model.

3 Results

Essentially the above described scenario has been simulated with normal cars and with CAVs and the two results have been compared. The results are shown in Tab. 2, distinguishing vehicles of the virtual population (these are vehicles circulating in the core area) and the vehicles of external demand (these are vehicles circulating also in the periphery).

Table 2: Performance results for virtual population (core area) and external demand (periphery).

Quantity	Normal cars	CAVs	Difference in %
Completed trips, external demand	44,941	47,590	5,89
Completed trips, virtual population	12,061	12,288	1,88
Av. Trip duration, external demand [s]	969.56	903.87	-6.77
Av. Trip duration, virtual population [s]	646.27	607.26	-6.04
Av. Waits, duration external demand [s]	72.16	65.89	-8,69
Av. Waits, duration virtual population [s]	135.30	130.76	-3.36
Av. speed, external demand [km/h]	45.00	54.25	20.56
Av. speed, virtual population [km/h]	26.21	28.19	7,55

The following observation can be made: for the scenario with CAVs, the completed trips (within 1 hour simulated time) is higher, the average trip duration is shorter, the wait times are shorter and the average speeds are higher with respect to the scenario without CAVs. There is a remarkable difference between the improvements made in the core simulation area (with a high node density) and the periphery (with a lower node density): the external car trips in the periphery do clearly profit more of CACs, while the advantages in the dense core area is less pronounced. The increase in completed trips indicates less congestion due to a higher road capacity. The increase in average speed (and consequently a decrease in average travel time) is mainly due to the higher speeds of the catchup followers, but also due to less congestion.

Average velocity and waiting times of bikes and pedestrians did not change significantly (improvements below 1% difference between normal car and CAVs), which is reasonable because both modes have their own network and do not interfere much with the road traffic, except at intersections. The waiting time of pedestrians (this is the time during pedestrians stand still) increases, but not significantly in the absolute sense (increase from 19.59s with normal cars to 20.30 with CAVs). This short average waiting time of pedestrians seems surprising and needs to be further investigated. Another reason for this small influence of CAVs on pedestrians could be because in the core area, where pedestrians are walking, the formation of platoons is less pronounced, as mentioned above. Also public transport average speed and travel time is almost unchanged by the presence of CAVs.

Instead, scooter seem to profit of the vehicle platooning with an increase of 5.28% in velocity and a decrease of 3.84% in trip duration. This means scooters can increase speed by following catchup vehicles, which do overspeed.

Concerning fuel consumption, the scenario with CAVs consumes 4.73% more fuel with respect to the ordinary car scenario, assuming that both scenarios use the same motor technology. Emissions are up 4.72% for CO_2 and 7.16% for all Particle Matter PM_x. Even though CAVs are expected to have cleaner motors or even full electric, it remains the fact that there seems to be an increase in energy consumption of CAVs with respect to normal cars, which is in line with the increase in average speed.

4 Conclusions

A realistic large-scale micro-simulation scenario during one rush hour in Bologna has been simulated – with and without CAVs. In the CAV scenario all private car trips of the normal scenario were substituted by CAVs. The simulated CAVS have been controlled by SIMPLA, with some modifications that avoid deadlock behavior. One of the most significant parameter of the platooning algorithm is the catchup speed which can be as much as twice the ordinary speed. A main limitation of SIMPLA is that it does not run well with the sublane model and it does not explicitly model communication links –these need to be modelled by parametrizing the car following model parameters of the used vehicles. SIMPLA has apparently no issues with string stability, most likely due to the use of simplified car follower models and the absents of communication delays between the vehicles.

The results indicate that the CAV scenario increases average speed by approx 6% in the periphery and 2% in the core area, made of a dense street network. Simulations showed that the presents of CAVs have a very limited effect on the speed and travel time of bikes, pedestrians and public transport. On the other hand, scooters can profit of the higher speed of catchup vehicles, which must overspeed in order to reach their lead vehicle.

The higher average speeds of CAVs is also responsible for a higher fuel consumption and emissions. Therefore, the role of the catchup speed is important as low catchup speeds will not lead to platoon creation over short distances and too high catchup speeds will lead to an increase of fuel/energy consumption, and will potentially compromise safety at certain locations. In summary, the speed gain of a few percent points can only be achieved by allowing extreme overspeed, otherwise the advantage of platooning would hardly be measurable.

The current study has some important limitations: 1) it considers only one rush hour and 2) no V2I communication is implemented; it can be assumed that if vehicles could communicate with traffic lights then this would further boost lane capacity at critical junctions of the network. For this reason it is planed to include the GLOSA module to adapt traffic light cycles to the arrival of vehicle platoons. A further project would be to introduce vehicle sharing, with the consequence that additional empty vehicles would circulate.

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